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CONTRACT NO. DA18 108 CML 533
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PROJECT NO. 4 80 02 025

ELECTRIC FILTER MATERIAL

FINAL REPORT TO
CHEMICAL CORPS
CHEMICAL AND RADIOLOGICAL LABORATORIES
ARMY CHEMICAL CENTER
MARYLAND

Arthur D. Little, Inc.

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Arthur D. Little, Inc.

THIRTY MEMORIAL DRIVE
CAMBRIDGE 42, MASSACHUSETTS

March 31, 1955

Chemical Corps
Chemical and Radiological Laboratories
Army Chemical Center
Maryland

<u>Attention: Private Bernard V. Gerber, Project Officer</u>

Gentlemen:

Attached herewith are seventeen copies of a final report entitled "Electric Filter Material", and a reproducible original.

This completes the work done under Contract DA18-108-CML-5332 dated January 27, 1954.

Respectfully submitted,

Arthur D. Little, Inc.

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I. SUMMARY

The purpose of this contract has been to determine the feasibility of using electrets or electret materials in aerosol filters, in order to improve efficiency through electrostatic precipitation mechanisms. Experimental work has gone forward in two phases, the first a direct applied approach and the second a more fundamental study of some of the factors involved. In the applied-approach phase, empirical attempts were made to produce electrets in forms useful for aerosol filtration and to observe improved performance with these materials. The results of these experiments revealed that the problem was considerably more complex than was originally anticipated. In no case was any enhancement of efficiency noted for known electrets, nor was any evidence developed that electrets might exist in forms other than the classical wax disc. Attention was therefore directed to the second phase, in which filter materials were studied which were believed to have electrostatic action of some sort and possibly characteristics of electrets.

Our attention has been concentrated mostly upon a study of resin wool filters and certain Vinyon microfibers which have recently been developed for the American Viscose Corporation. Although the resin wool material could hardly be composed of electrets, it is reported to utilize electrostatic mechanisms of particle collection, so that it bears a close relationship to the problem in question. The Vinyon fibers, which are spun in air from a solvent solution in the presence of an electric field, have filtering properties similar in many respects to those of resin wool material. Since the manufacturing conditions are similar to those required for electret formation, and since the aerosol filtration characteristics are similar to those of known electrostatic filters, a considerable portion of the work on this contract has been devoted to a study of Vinyon.

During this work, it has become more and more evident that the factors involved in particle collection by fibrous media having electrostatic properties are very poorly understood. In order to develop a satisfactory filter incorporating electrically charged materials, it is first necessary to understand certain fundamental physical principles, such as:

1. The mechanisms of particle attraction and precipitation;

2. The magnitudes of the forces involved;

3. The nature of the charges trapped on the filter material and perhaps on the aerosol;

4. The effect of the dielectric constant of the aerosol;

5. The effect of the particle size of the aerosol;

6. The role of "bounce-off" phenomena; and

7. The effect of discharging mechanisms on all of the variables of the system.

Because of the complexity of the problem, work under this contract has not as yet established the feasibility of utilizing electrets in aerosol filters. At the present time, it appears that the resin-wool and Vinyon fibers do show an enhancement in filtration properties because of electrical forces, but the actual mechanisms involved are still not clearly understood. The behavior of these materials bears a superficial resemblance to that which might be expected of fibrous electrets, but closer study shows many discrepancies in this simplified concept.

A filter has been made from Vinyon by subjecting the material to thermal and electrical conditions favorable to electret formation. This filter shows external electret properties and a significant enhancement of efficiency over a control. However, the available time has not yet permitted a sufficiently thorough analysis of this type of filter.

It is recommended that a considerable study program be carried out, so that the nature of the electrostatic phenomena involved can be understood. Most of the investigation to date has served to reveal previously unsuspected complexity in behavior which is not rationalizable in terms of the classical electret concept.

II. INTRODUCTION

A. Scope of Work

The objectives of the work described in this report were:

1. To survey and determine the feasibility of the use of electret materials for aerosol filter media; and

2. To develop and fabricate promising electret filter materials and test their aerosol filtering capabilities, under various conditions, in comparison with standard Chemical Corps C6 filter paper.

B. Background and History

1. Electrets

In 1920, Mototaro M. Eguchi(1) discovered that when certain combinations of waxes and resins are solidified in a strong electric field, a "permanently polarized dielectric" is obtained. Eguchi found that such dielectric plates possessed a surface charge which, when discharged with a bunsen flame or x-radiation, would gradually recover. The charge was found to be maintained without significant change for long periods of time, provided that the dielectric was stored between short-circuited metallic keepers. It was also observed that cutting away the surface with a sharp knife did not permanently affect the polarization. Eguchi concluded that the observed phenomena were entirely different from any surface electrification and that the effects were indeed produced through some sort of permanent volume polarization. Due to the analogy with a permanent magnet, Eguchi proposed the name "Permanent Electret" or simply "Electret" for such a dielectric.

Eguchi's efforts were met with considerable skepticism at the time of their publication in the Philosophical Magazine in 1925, and comparatively little work has been done on the subject since then. Those who have studied electrets apparently started out with the thought in mind of disproving the earlier work. Instead, however, the results have been confirmed, and new peculiarities in behavior have been reported. Among others, Gemant(2) observed that the initial charge on an electret usually bears the

(1) Numbers in parentheses refer to Appendix B, Bibliography.

opposite sign to that of the adjacent forming electrode. He noted that this charge decreases shortly after manufacture, and a charge of opposite sign appears, which is maintained for long periods of time. The first condition was termed the heterocharge, and the latter the homocharge.

In the last 20 years, several theoretical explanations of the phenomena involved in electret behavior have been proposed.[3] To date, however, there is still no universally accepted explanation, so that there is still a great need for basic research on electret mechanisms. During this same period, various practical applications for electrets have been proposed and, in some cases, demonstrated.[4, 5, 6, 7] These include electrometers, microphones, radiation dosimeters, mass spectrometers, and batteries. In World War II, the Japanese actually used microphones incorporating electrets,[3] but this is apparently the only occasion to date in which electrets have been used for a practical purpose on a relatively large scale.

2. Electret Filters

a. Electrets as Aerosol Filters. In 1927, a German patent[8] was filed by a Swedish firm which claimed a respirator or gas mask filter made up of or incorporating electrets in plate or granular form. No reference to the use of such filters has been found, nor has any information on the performance of such units been located.

b. Resin Wool Filters. In 1932, Nicolai Hansen secured a patent[9] on a filter incorporating wool fibers treated with certain resins. His product had the advantage of yielding a much higher efficiency filter than is normally attainable with wool in any form, but with a negligible increase in pressure drop. In the years since Hansen's discovery, this type of filter has been exploited, studied, and improved in many European countries. In their present state of development, the best resin wool filters are produced by dusting or solvent-treating wool fibers or felts with certain resins and subsequently carding the treated fibers or otherwise mechanically handling them. This latter process presumably serves to frictionally transfer electric charge from the resin particles to the wool, and perhaps accounts for the high efficiency of the resultant filters. In addition to the fact that the filtration efficiency is vastly improved, the units have been reported to have a shelf life of 10 years or more. Due to this latter fact, it has been suspected that some process other than mere surface electrification of the resin particles must be involved, since a frictional surface charge would not normally be expected to last for more than a short time under normal conditions. This superficial resemblance to electret behavior has led some investigators to assume that the resin wool filters are indeed composed of electrets.

Considerable work on this subject has been done at the British Experimental Station at Porton, England.[10] The conclusion of personnel there was that the resin wool filter functions by means of electrostatic attraction and precipitation of aerosol particles due to the frictionally applied charge on the resin and an induced charge of opposite sign on the wool. They attributed the long shelf life of the filters to the extremely high surface resistivity of the resin. They attempted to show that present methods of measuring the resistivity of dielectric material were inadequate, and presented some evidence that volume resistivities as high as 10^{21} ohms-cm were possible and might account for the long shelf life. They also attempted to develop a method of predicting the potential usefulness of various resins in these filters by correlating efficiency with resistivity. These attempts failed, however, because accurate and reproducible measurements could not be made. The hypothesis that electret-type mechanisms might be involved was discarded in favor of the frictional electrification theory, due to the accumulated evidences in the latter's favor. Appendix A gives a summary of the findings at Porton.

c. American Viscose Electrified Microfibers. Certain synthetic vinyl fibers which have recently been developed for the American Viscose Corporation are spun from solution and dried and collected in a strong electric field. This system has been used successfully in the production of dry formed fibrous mats from Vinyon, Dynel, Acrylonitrile, and other resins. The mean fiber diameter produced in this system varies somewhat, but is in the order of one micron.

The fibers apparently have the ability to maintain a very high surface charge for long periods of time, and when fibrous mats of this material are tested on DOP smoke, they show an abnormally high initial efficiency, which drops off quite drastically with time. Although the mechanisms involved in this behavior were not known, it was suspected that electret-type action might be involved. This line of reasoning was logical, since the conditions of manufacture were similar to those of electret formation, and the surface charge and filtration behavior were indicative of appreciable electrification.

With the exception of the three instances described above, no attempts to use electrets as aerosol filtering media are known.

III. THEORETICAL CONSIDERATIONS

A. Mechanisms of Charge Production on or in Dielectric Materials

1. Frictional Charging

Probably the most frequent method of charge generation on surfaces is frictional electrification. Charge is produced in this case by the transfer of electrons from the surface of one substance to another as the two surfaces are brought into intimate contact and then separated. This transfer leads to an excess of electrons on one surface (a negative charge) and a deficiency of electrons on the other surface (a positive charge). At the instant of charge transfer, the potential difference between the two surfaces may be very small, probably considerably less than one volt. When the two materials are subsequently separated, the potential difference increases in proportion to the distance of separation, just as it does when the plates of a charged condenser are separated without allowing the charge to diminish.

2. Permanent Polarization

Certain dielectric materials made up of polar molecules will tend to become oriented if an external electrical stress is applied. That is, if such materials are placed in an electric field, the polar molecules will tend to rotate so that the positive poles face the negative electrode and the negative poles face the positive electrode. In addition, under the influence of the field, ions of opposite polarity are drawn apart and the result is a distinct separation of charge. If the field is applied when the dielectric is melted or at an elevated temperature, the mobility of the ions and molecules is sufficient to allow significant orientation. If the dielectric is then solidified and cooled with the field still applied, the polarization may be "frozen in," so that a more or less permanent effect is produced. This effect results in an excess of charge on the faces of the dielectric and thus produces in effect, a gross dipole with positive charge on one surface and negative charges on the other.

While the polarization may be essentially permanent (it is not completely permanent, since the molecules have some mobility, even in the solid state), the charge on the surface will disappear under normal conditions, due to the conductivity of the air. That is, ions in the air will gradually neutralize the charge on the surfaces until no residual charge remains.

3. Trapped Net Charge

It is conceivable that electrons or electron deficiencies may become trapped in the lattice of a dielectric material where the charge mobility is essentially zero. Such a net charge or unequal charge distribution may be permanently frozen in. Even so, it would be expected that gaseous ions would soon adjust the surface charge distribution in such a way as to produce a net external field of zero everywhere.

B. Heterocharge and Homocharge in Electrets

As described in Section II-B-1, many electrets show a reversal of polarity of charge shortly after manufacture. That is, the charge originally present has the opposite sign to the adjacent forming electrode, and is termed the heterocharge. In a matter of hours (or a few days at most), this charge decreases to zero and then builds up again with opposite polarity. The latter condition is essentially permanent, and is termed the homocharge.

Although several theoretical explanations of this behavior have been advanced, there is no completely satisfactory interpretation available to date. It is generally conceded that the reversal of polarity is due to two independent charge-producing mechanisms, one of which decays to zero so that the other overcomes it and thus causes the reversal and secondary build-up.

C. Factors Involved in Electrostatic Collection of Particulate Matter

Electrostatic collection of aerosol particles depends primarily upon attractive forces between the collecting surface and the particle. These forces result in migration of the particles from the gas stream to the surface, where they impinge and are collected. Although this principle is quite straightforward, many factors which are very poorly understood are involved in electrostatic filtration by fibrous materials.

Of prime importance is the relationship between the electric field strength around the fibers and the charge on the aerosol. A charged particle near a charged fiber will be collected only if the forces involved are great enough to bring the particle to the fiber before the gas stream carries the particle away. The force, in turn, depends upon the field strength around the fiber, the size, charge, and dielectric constant of the particle, and the distance of the particle from the fiber. In order to understand and appreciate the mechanisms involved in this type of filtration,

knowledge of the relative magnitude of the variables involved is required. Although the British at Porton attempted to evaluate some of these factors for resin wool filters, they apparently failed to evaluate the effect of charge distribution or properties of the aerosol. They apparently assumed the dipolar charges were first induced on the aerosol by the field around the fiber. The particles thus charged were then precipitated on the filter, due to the resultant attractive forces. It is probable, however, that the methylene blue aerosol, which was used exclusively in their tests, was highly charged when it was formed. That is, the particles are formed by spraying or atomizing a solution of methylene blue and evaporating the solvent from the droplets. This process results in solid particles of about 0.2-micron diameter. In such a spray process, the droplets are almost invariably charged as they pass through the nozzle. As the solvent evaporates, it leaves a smaller solid particle, but the charge remains and is thus considerably concentrated. For this reason, it does not appear that the Porton results are conclusive.

Although it is true that resin wool filters show a high efficiency on atmospheric dust, which is generally composed of approximately 50 percent neutral particles, there is no concrete evidence that induced dipolar effects are present to account for the high collection efficiency. Consequently, it seems apparent that this field of aerosol filtration would profit by a comprehensive study of the various factors involved. This study would of necessity include a series of calculations designed to determine the field strengths and particle characteristics necessary to account for the observed behavior of various fibrous electrostatic media. Such calculations might go far toward providing confirmation of the mechanisms involved, or they might lead to possible alternative theories.

D. Bounce-off Phenomena

It is a common observation that drops of water and other liquids sometimes do not coalesce with other drops on a large body of the same liquid. For example, drops of spray from the bow wave of a motorboat can frequently be seen to skate over the surface of the water for some distance. Rayleigh[11] has shown that the drops of water from a small vertical jet do not coalesce, but bounce off each other like many small tennis balls. He has also shown that this bounce-off completely disappears in the presence of small electric fields.

Although the phenomenon of bounce-off is presently very poorly understood, there is a possibility that it plays a significant role in aerosol filtration, especially where fibrous electrostatic media are concerned. It is possible that oil-smoke aerosols of such materials as dioctyl phthalate

may exhibit these bounce-off properties. If they do, the effect might be twofold. That is, in the initial period of filtration, when electric fields around the fibers of the filter are present, bounce-off resulting from collisions of smoke particles might be reduced. Collisions might result in coalescence of aerosol particles, and thus increase the average particle size. The larger particles thus formed would have a greater probability of impinging on a fiber and being collected. The result of such a mechanism would be a higher efficiency than normal.

As this filtration process continues and the fibers are coated with collected oil, the collection surface becomes a semiconductor, and the charge is neutralized. Thus, in the latter stages of filtration with little or no field to act upon the particles, no coalescence would occur. In addition, since the fibers are coated with the same material as the aerosol droplets, it is possible that particles which do impinge on the fibers exhibit the same phenomena and bounce back into the air stream.

The net result of such phenomena would be a high initial efficiency, followed by a steady drop-off as the fields are destroyed and the fibers are coated. This behavior is precisely the type exhibited when electrostatic filter media are tested on oil smokes.

Although there is little evidence available to confirm it the hypothesis described above remains a distinct possibility and should be evaluated. Also, if the calculations discussed in Section III-C indicated that the electrical forces involved are insufficient to account for the observed high efficiencies, an explanation based upon bounce-off would provide a logical alternative.

IV. APPARATUS AND EXPERIMENTAL PROCEDURES

A. Measurement of Surface Charge

Charges on the surface of various materials studied in connection with this contract were measured with a Keithley vacuum tube electrometer and a Faraday cage. The body whose charge was to be measured was suspended from a grounded, spring-loaded clamp in the top of the metal cage. The electrometer was positioned so that the high-potential electrode entered the bottom of the cage, and was fitted with a plate parallel to the surface of the body whose charge was to be measured. When the spring-loaded clamp was forced down, the field produced by the charged surface approached the electrometer electrode, so that the field strength increased and caused a deflection of the meter needle. When the clamp was released, the needle returned to zero. By maintaining the distance of clamp travel and the overall geometry constant, reproducible meter readings were attained. These readings were proportional to the charge on the surface of the material. (See Figure 1.)

B. Measurements of Discharge Currents

Continuous currents resulting from exposure of charged surfaces to radioactivity were measured with a modified version of the same apparatus used to measure the surface charge. In this arrangement, a decade shunt resistance was connected across the terminals of the electrometer so that currents as small as 10^{-14} ampere could be detected. A conducting plate between the charged surface and the electrometer electrode was formed by shielding a radioactive probe so that the rays were focused on the surface of the discharging material. The resulting neutralized charges were thus channeled through the meter and were measured as currents. (See Figure 2.)

C. Dioctyl Phthalate Smoke Generator

The aerosol filtration ability of various materials has been tested primarily with a smoke generator which produces 0.3-micron dioctyl phthalate particles. The arrangement is such that the oil is vaporized, and is then condensed and mixed with air to form the test aerosol. The smoke is then passed through the sample filter and into a light-scattering chamber, where a photocell and amplifying circuit produce a direct reading of the percent of smoke penetrating the filter. A water-filled manometer is used to measure the pressure drop across the filter. (See Figure 3.)

FIGURE 1

APPARATUS FOR MEASUREMENT OF SURFACE CHARGE

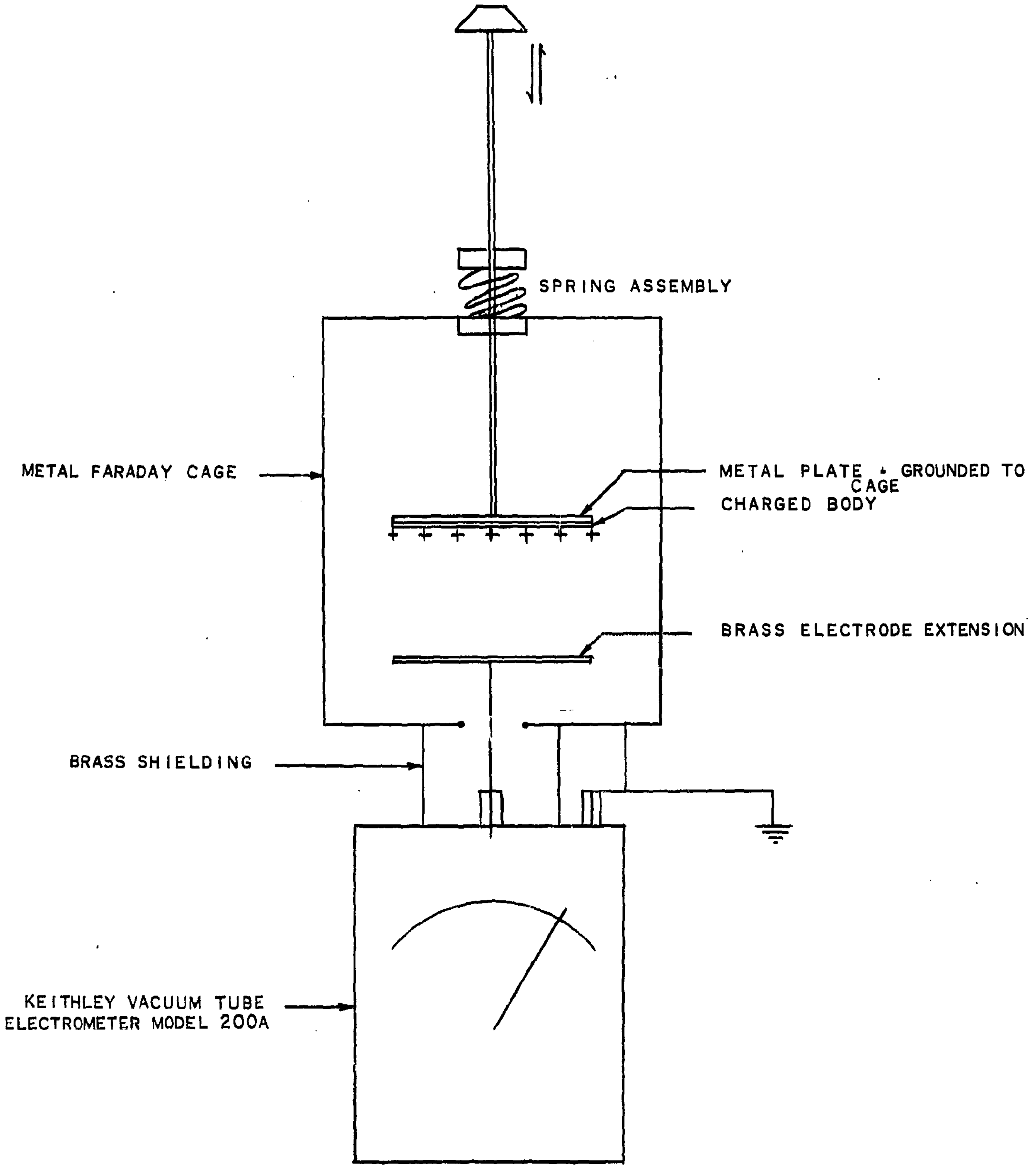

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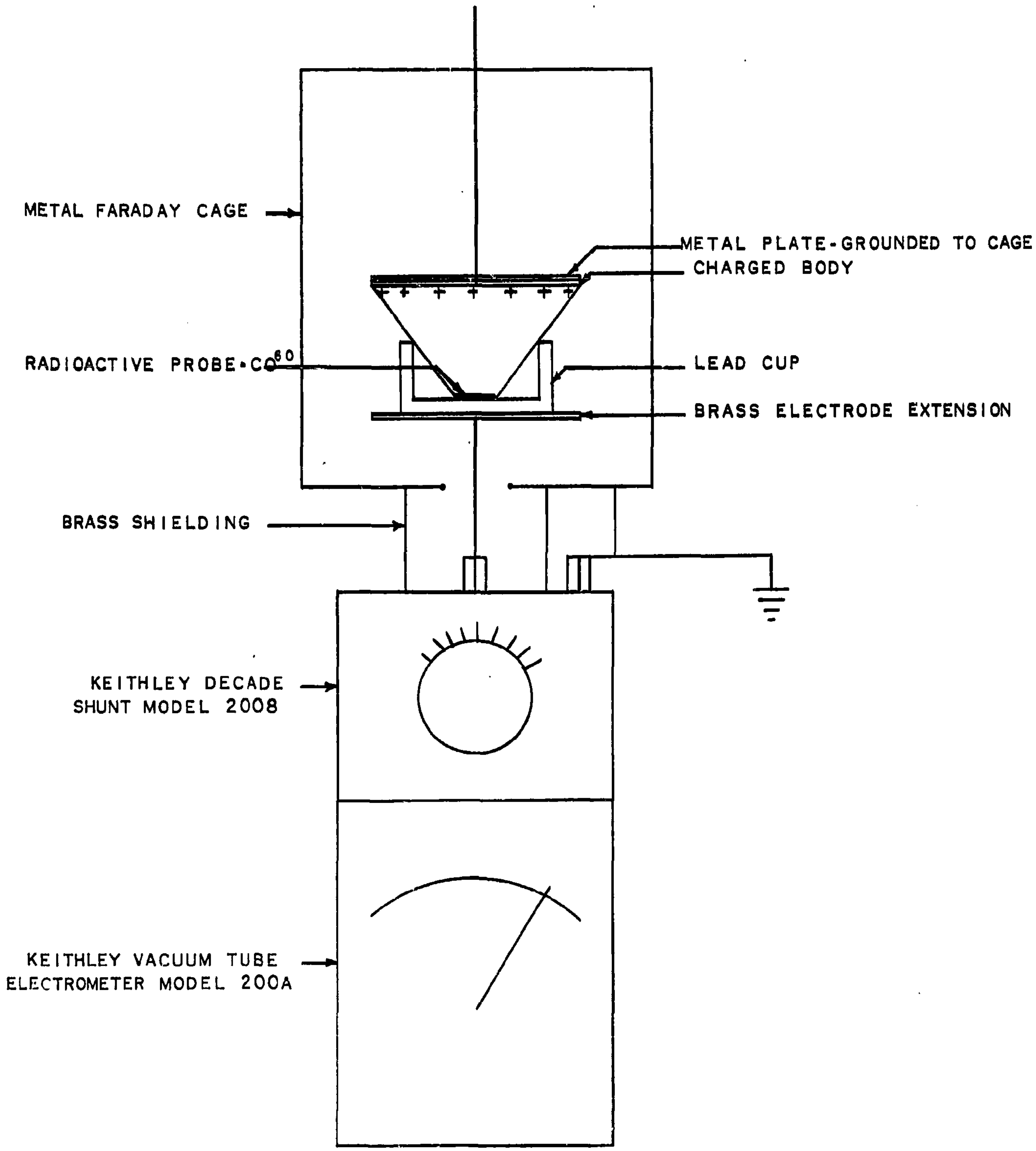
FIGURE 2

APPARATUS FOR MEASUREMENT OF CONTINUOUS DISCHARGE CURRENTS



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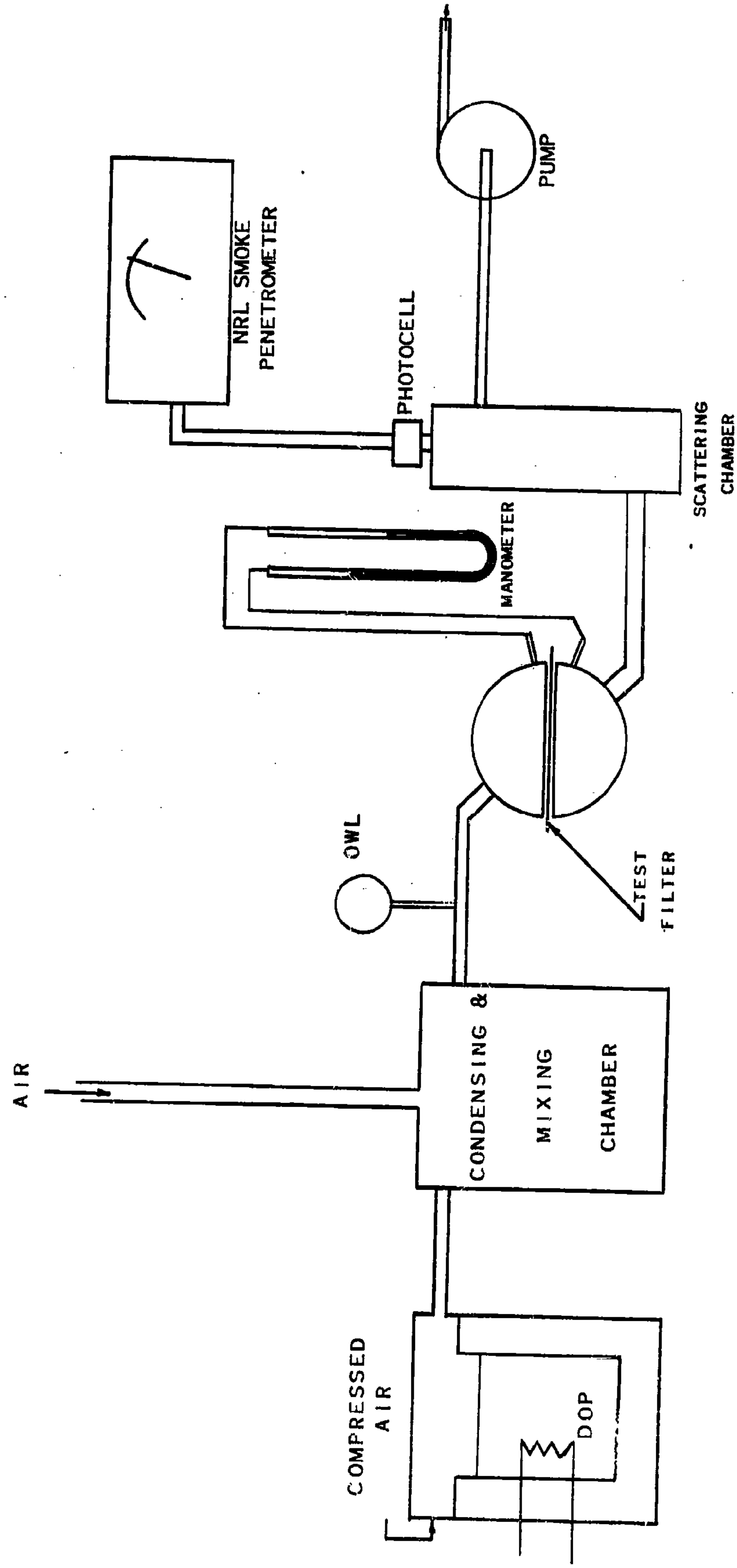


FIGURE 3

DIOCTYL PHTHALATE SMOKE GENERATOR

The usual test procedure first involves passing the smoke stream through the sample holder without a filter in place, so that the meter may be standardized for 100 percent penetration. The usual flow rate is 85 liters per minute, which is equivalent to a linear velocity of 28 ft per minute across a sample 4-3/8 inches in diameter. The sample is then put in place and the smoke stream is introduced into the system. The percent penetration and the pressure drop can then be read directly.

The particle size of the aerosol may be varied by changing temperature conditions and flow rates, but it is usually adjusted to 0.3 micron.

D. Fiber Extrusion in an Electric Field

A small pressure extruder was built, in order to manufacture synthetic fibers. The extruder consisted of a steel piston in a steel cylinder with a nozzle at its base. Heat and pressure were applied simultaneously in a Carver hydraulic press. Heat was supplied by heated platens on the press and also by a high-resistance wire winding around the cylinder. A second resistance heater was used to control the nozzle temperature. When the heat and pressure were applied, the resin was melted and forced through the nozzle as a monofilament. As the filament was extruded, it was drawn down by means of a spindle on a variable-speed takeup motor. Thus, by varying pressure, temperatures, and motor speed, the fiber diameter could be controlled. (See Figure 4a.)

The apparatus was arranged so that a direct-current field could be applied across the fiber as it left the nozzle and solidified. The electrode assembly could be arranged in two ways, in order to provide a field--either perpendicular to, or parallel with the line of flow of the fiber. For a perpendicular field, the assembly consisted of two brass plates parallel with the fiber, as shown in Figure 4b. For a parallel field, the fiber passed through a hole in a brass plate perpendicular to the fiber. The extruder was grounded, to provide the second electrode. (See Figure 4c.)

E. Determination of Magnitude of Charge on Single Fibers

Surface charge on single fibers has been studied microscopically with the aid of a special cell in which the fiber is supported. In this arrangement, the fiber is mounted horizontally on a glass or copper filament between two brass electrodes. When a potential is applied across the electrodes, the charged fiber deflects toward the electrode of opposite polarity. When the potential is removed, the fiber returns to its original position. The switching arrangement was such that the polarity could be reversed, and the fiber

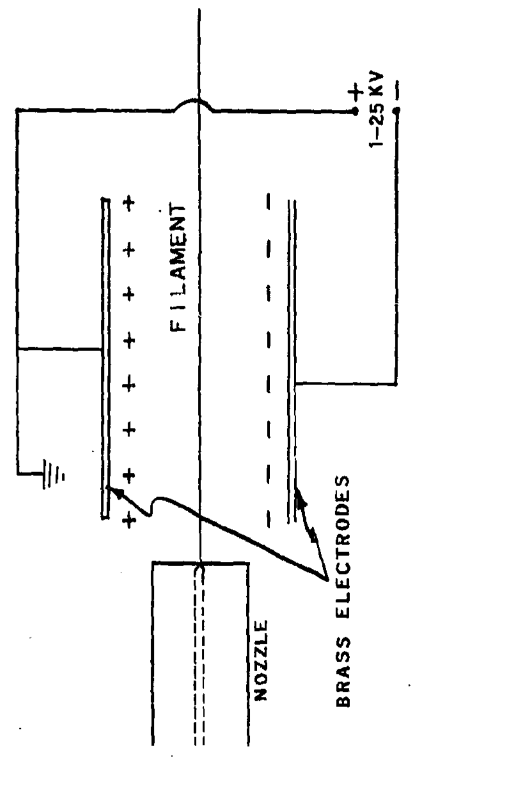


FIGURE 4b

FIBER FORMATION IN FIELD PERPENDICULAR TO FIBER

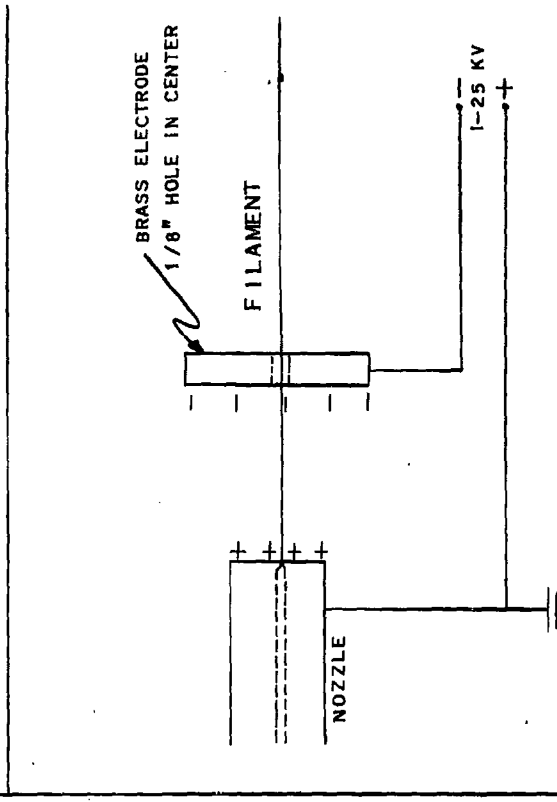


FIGURE 4c

FIBER FORMATION IN FIELD PARALLEL WITH FIBER

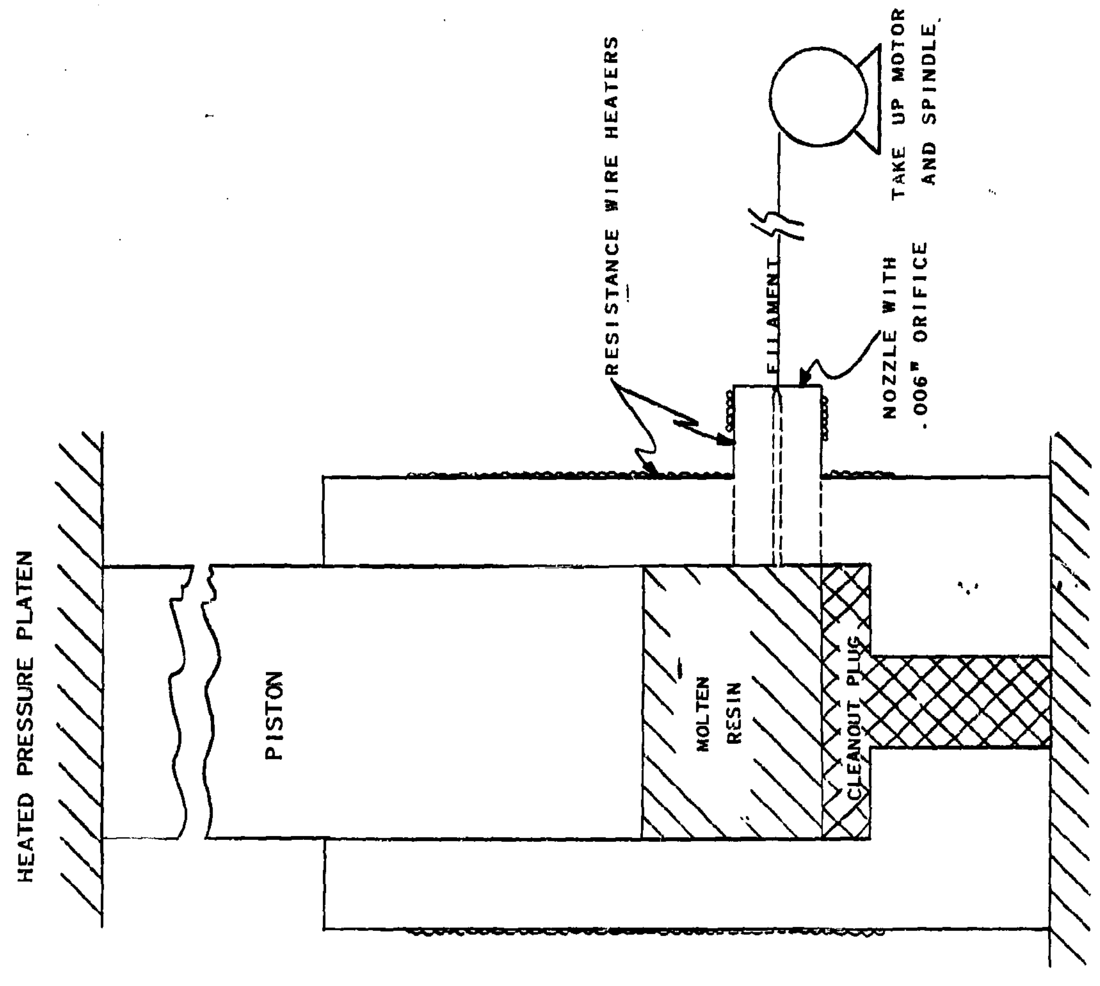


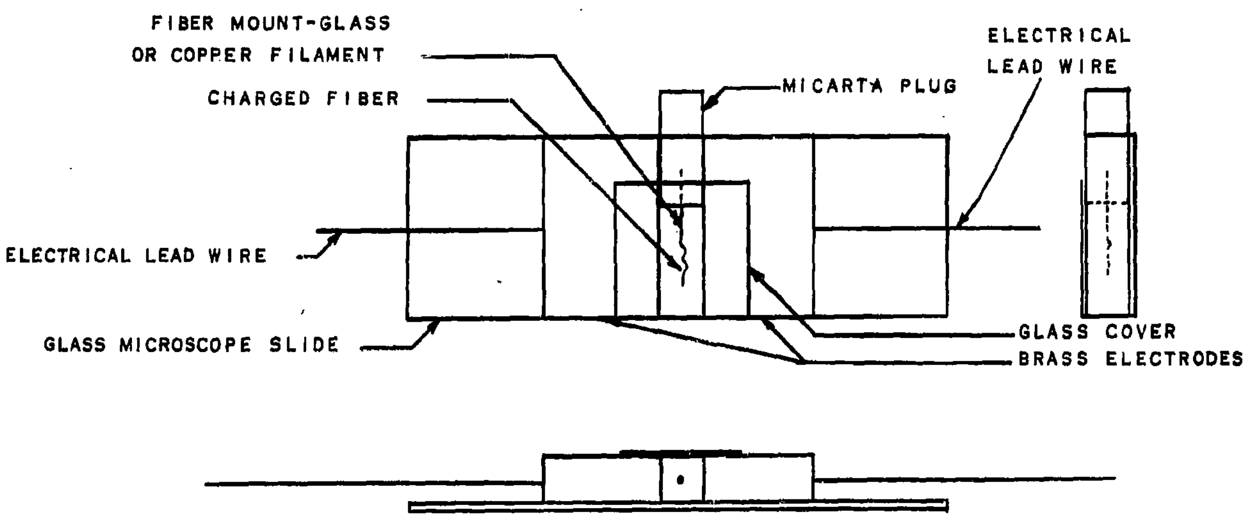
FIGURE 4a

FIBER EXTRUSION APPARATUS

could deflect in either direction. The deflection of the fiber produced by a constant voltage of 135 volts was measured with the aid of a calibrated reticule in the eye piece of the microscope at a magnification of 150 diameters. The deflection of the fiber produced by the field is proportional to the charge on the fiber. (See Figure 5.)

FIGURE 5

APPARATUS FOR MEASUREMENT OF CHARGE ON SINGLE FIBER



V. EXPERIMENTAL RESULTS

A. Electrets

Initial experimental work was done with disc-type electrets manufactured in this laboratory, in order to confirm the more classical experiments and to gain familiarity with the phenomena involved. Discharge and recovery characteristics were observed with the aid of the vacuum-tube electrometer in conjunction with a Faraday cage. In addition, continuous discharge currents were produced by means of a small radioactive probe irradiating the surface of the electret within the metal cage. In order to throw some light upon the phenomenon of charge generation within an electret, the apparatus was arranged so that the temperature of the electret could be held constant at any desired value. It was expected that current flow would be dependent on temperature if a diffusive process requiring an activation energy was involved in the charge-generation process. It was found that the charge-producing mechanism of typical wax-rosin electrets was extremely temperature-dependent. That is, the discharge currents and the rate of recovery of charge were greatly accelerated at elevated temperatures and retarded at lower temperatures. (See Figures 6 and 7.)

B. Electrets as Aerosol Filters

1. Granulated Electrets

As a reasonable first step toward the ultimate objectives of the contract, a direct applied approach based on the German patent described in Section II-B-2 was attempted. Several electrets of similar history were cooled and pulverized to a granular state. The fraction passing a 16-mesh screen but retained on a 40-mesh screen was collected and made up into filter cartridges. Similar cartridges were made from unelectrified wax. These units were then tested on 0.3-micron dioctyl phthalate smoke. It was realized that filters manufactured from granular materials are inherently inefficient, but it was hoped that if any benefits were to be derived from electrets in this form, they would be distinguishable through improved performance. It was also not known whether the electrets would retain their electrification in such a subdivided form. It was believed, however, that if aerosol filtration were being enhanced by the presence of electric forces, two phenomena would be observed in the smoke penetration test: first, the initial efficiency of the electret cartridge would be significantly higher than that of the control; and, second, the efficiency of the electret unit might be expected to fall off with time, due to the neutralization of charges by the DOP smoke. Neither of

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FIGURE 6

EFFECT OF TEMPERATURE ON ELECTRET DISCHARGE CURRENTS

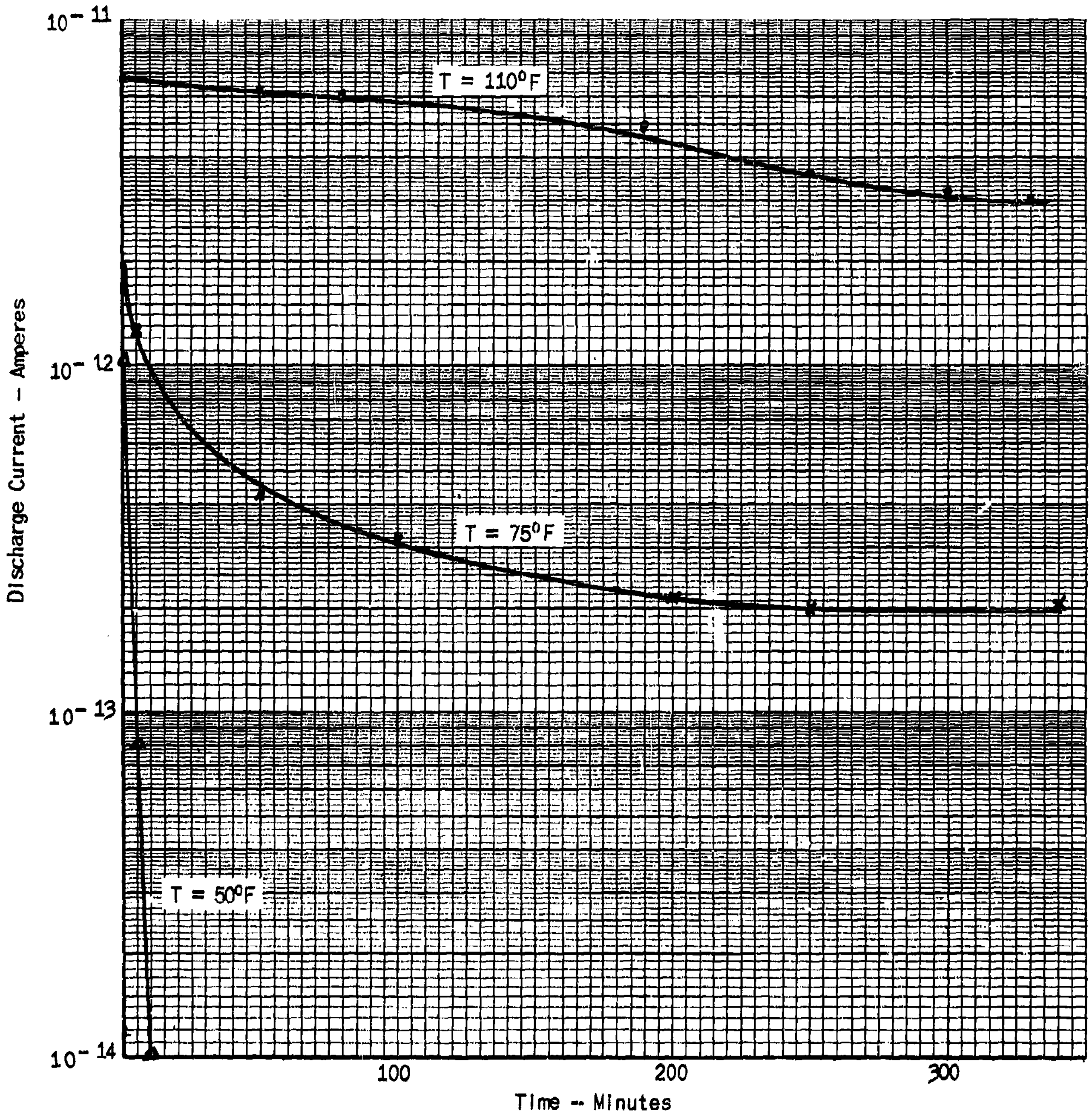

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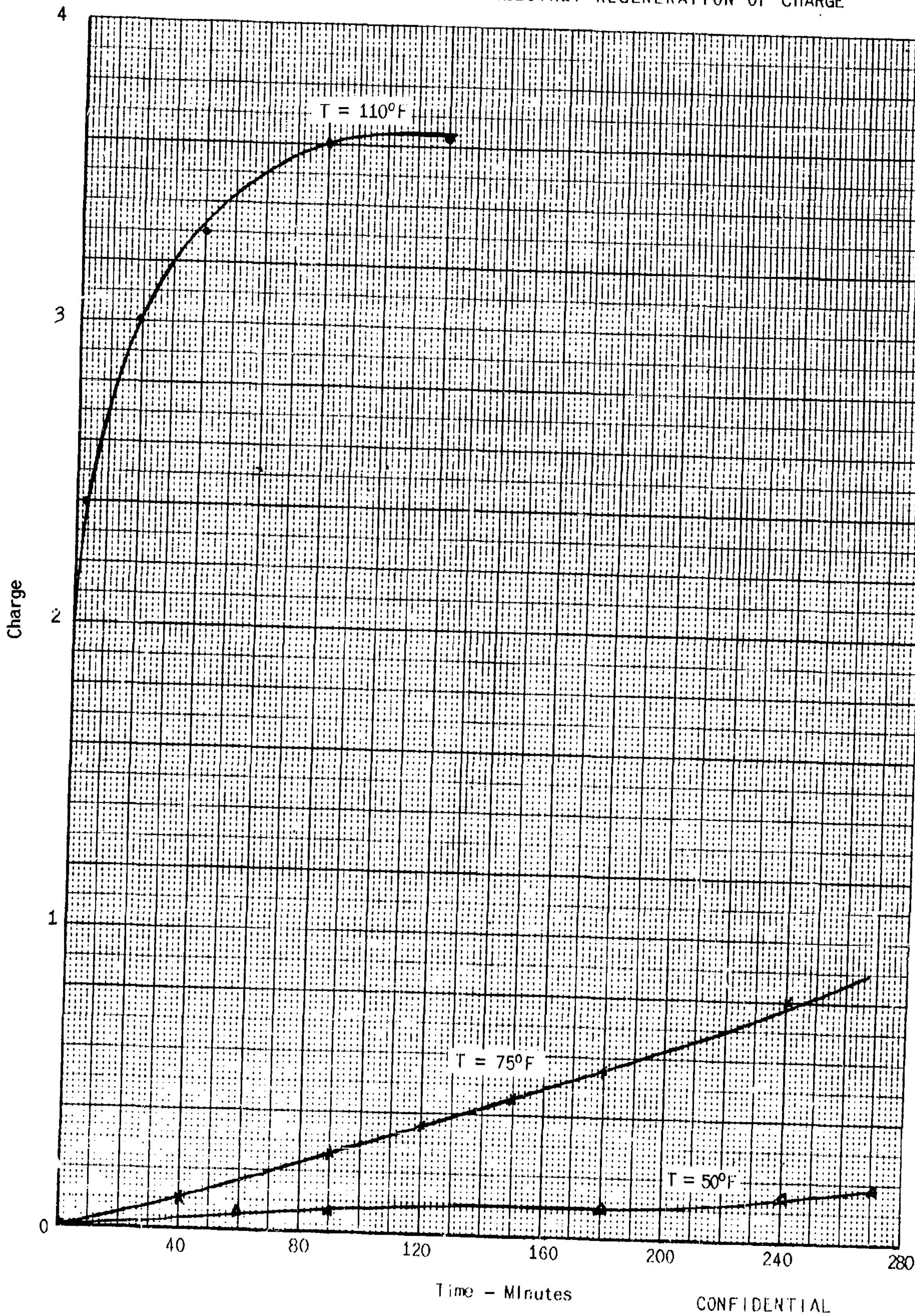
FIGURE 7

EFFECT OF TEMPERATURE ON ELECTRET REGENERATION OF CHARGE



these effects was noted. In both cases, the efficiency was essentially constant with time, and no significant difference between these efficiencies was noted. These results may be interpreted in two different ways: either the electret discs lose their electrical properties or external fields when they are subdivided; or the fields present are too small to influence aerosol particles. Unfortunately, it is not possible to test the surface charge characteristics of such small particles in the same manner as with the gross discs. Because of the difficulties encountered in the interpretation of results, it was decided to investigate electrets in other forms.

2. Fibrous Electrets

The only available indication that it might be possible to form electrets in fibrous form was the American Viscose fibers. It was thought, however, that it would be advantageous to form fibers from a hot melt instead of from solution, and to solidify the filament in an electric field. In this manner, the conditions of manufacture would be more analogous to those of disc electrets, except that the time element would be greatly reduced, since cooling would be more rapid.

The first task in this approach was to find a synthetic resin or resins capable of forming both good fibers and strong electrets. The polyvinyl acetate resin, Gelva V-7, used with much success in the formation of disc electrets at the University of Kansas,(4) was found to be a comparatively poor fiber-former, in that the fibers were too soft and tended to lose their structure when handled. Two synthetic resins were found, however, which appeared to fulfill the necessary requirements. These were Acryloid B-72, an acrylic manufactured by Rohm & Haas Co., and FM-6501 alcohol-soluble nylon, manufactured by E. I. du Pont de Nemours & Co.

The small pressure extruder described in Section IV was used to manufacture the fibers. The electrodes providing the field were mounted either perpendicular to or parallel with the fiber, so that any effects due to the direction of polarization could be noted. Field strengths of from 1-10 kv/cm were used during the manufacture of the fibers. In no case was any evidence of permanent electrification observed. When surface characteristics were investigated in the Faraday cage, a small surface charge was invariably present on the surface of the fibers, due to frictional electrification during the extrusion process, but no indication of spontaneous regain of charge after discharge was observed. In addition, experimental filters made from these fibers showed no improvement in efficiency over similar units made from fibers formed without the applied field. Considerable effort was expended toward reducing the fiber diameter from 20-30 microns to less than 10 microns, both to increase the inherent filtration ability of the fibers

and to approach the properties of the American Viscose fibers more closely (average fiber diameter = 1 micron). These efforts met with little success, however, and even the smallest fibers attained (15-20 microns) showed no evidence of electret properties. On the basis of these results, work with spinning fibers from the molten state was discontinued.

3. Impregnated Filters

As a third attempt to evaluate electrets as aerosol filters, it was proposed that low-efficiency filter papers might be impregnated with a solvent solution of an electret-forming resin and subsequently dried in an electric field. It was hoped that this procedure might lead directly to the formation of a filter incorporating electrets. Accordingly, handsheets were made up from combinations of glass, asbestos, and kraft fibers, with an efficiency of approximately 50 percent on DOP. These papers were then impregnated with solutions of electret-forming materials, such as carnauba wax and Gelva V-7 polyvinyl acetate. The solvent was then evaporated in a field of 8-10 kv/cm. Although this procedure is not a standard or proven method of manufacturing electrets, it is similar to the process used in making Vinyon fibers and was consequently considered to be a promising avenue of approach. Again negative results were obtained. Both the electrified papers and the controls showed a slightly lower efficiency when impregnated. The papers dried in the field showed no enhancement in performance and no drop in efficiency with time. In addition, no external electrification or electret behavior was exhibited when the surface was examined for charge in the Faraday cage.

Because all attempts to form electret filter material led to a negative result, it was thought advisable to shift away from the direct applied approach to the problem to a more fundamental viewpoint. Since it was presumed that the fibrous mats made for American Viscose functioned as aerosol filters through electrostatic action, and since it seemed quite likely that electret action was involved, attention was directed toward a study of these materials. In addition, it was decided to study resin wool filter behavior in conjunction with the work on the American Viscose material. It was hoped that such a study of existing electrostatic filter material would be of benefit in predicting the potential use of electrets.

C. American Viscose Electrified Microfibers

The fibrous mats described in Section II-B-2-c have been made from a number of synthetic vinyl resins, including Vinyon, Dynel, and Acrylonitrile. All of these materials possess a very high surface charge

and show anomalous filtration ability in that their initial high efficiency on DOP decreases with time to a value that might be considered normal, as judged from the mechanical properties of the mats. The Vinyon material in particular shows the greatest effect of this type. (See Figure 8.) Consequently, most of the work done on the American Viscose material has been with Vinyon.

1. The Surface Charge

Probably the most obvious property of the Vinyon material is its extremely high surface charge. This charge is observed whenever a section of mat is moved or handled, due to the large attractive and repulsive forces present. In addition, the charge is easily detected with an electrometer and is usually of negative polarity.

a. Effect of Radiation. Since it was assumed that the appearance of the surface charge was responsible for the unusual filtration behavior of Vinyon, initial experiments were carried out to determine the effect of neutralizing the surface of the mat with radioactivity. That is, if a charged body is exposed to ionizing radiations, such as x-rays or radioactivity, the surface of the body is rapidly neutralized, due to the migration to the surface of ions produced by the radiation. A low-intensity (about 4 microcuries) cobalt^{60} source (a gamma-ray emitter) was used for the neutralization. Several samples were exposed to the source for periods up to 65 hours and subsequently tested on DOP. The surface charge was found to be neutralized essentially completely, as determined by the electrometer. The filtration ability was completely unaffected, however. The resulting efficiency-time curves were almost identical with the curve for Vinyon shown in Figure 8.

In an effort to explain the results and determine the nature of the surface charge, several control experiments were conducted in the Faraday cage-electrometer setup. It was found that the charge could be completely neutralized by the Co^{60} source in 20 or 30 minutes and that there was apparently no tendency for the charge to regenerate in a manner analogous to electrets. In order to obtain a clearer picture, the apparatus was arranged so that discharge currents could be measured continuously, as described in Section IV. Figure 9 shows the results of a series of experiments with this arrangement. After the original discharge current, represented by Curve A, the sample was then left untouched in the cage for 2-1/4 hours. The radioactive source was then replaced, and the discharge current represented by Curve B was produced. At this point, the sample mat was gently rubbed with a glass rod, in order to electrify the surface frictionally. The subsequent discharge current is represented by Curve C. Curve D is the current

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FIGURE 8

FILTRATION BEHAVIOR OF AMERICAN VISCOSE MICROFIBERS

I - Vinyon
II - Dynel

Test Aerosol - 0.3μ Dioctyl Phthalate Smoke

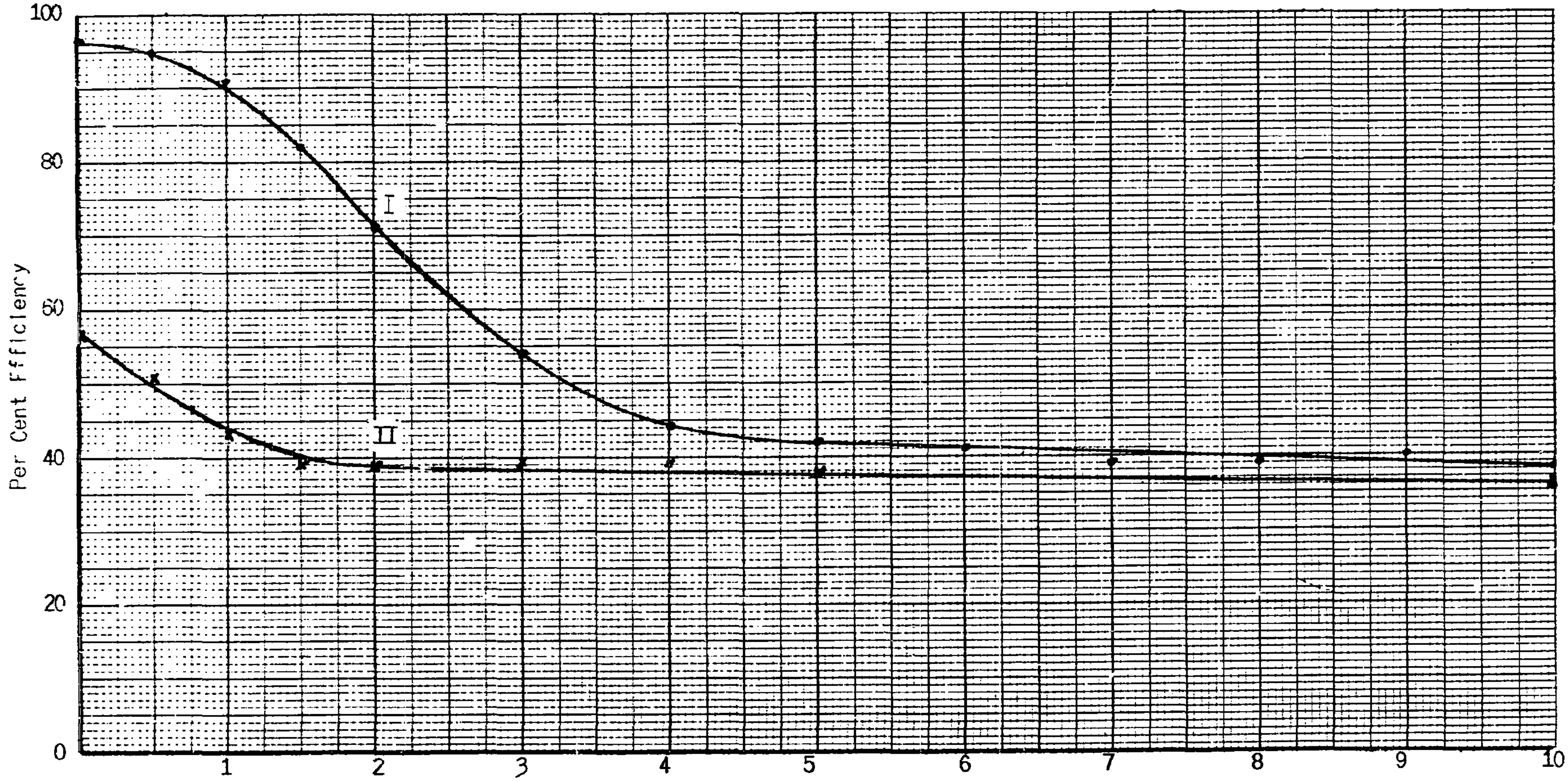

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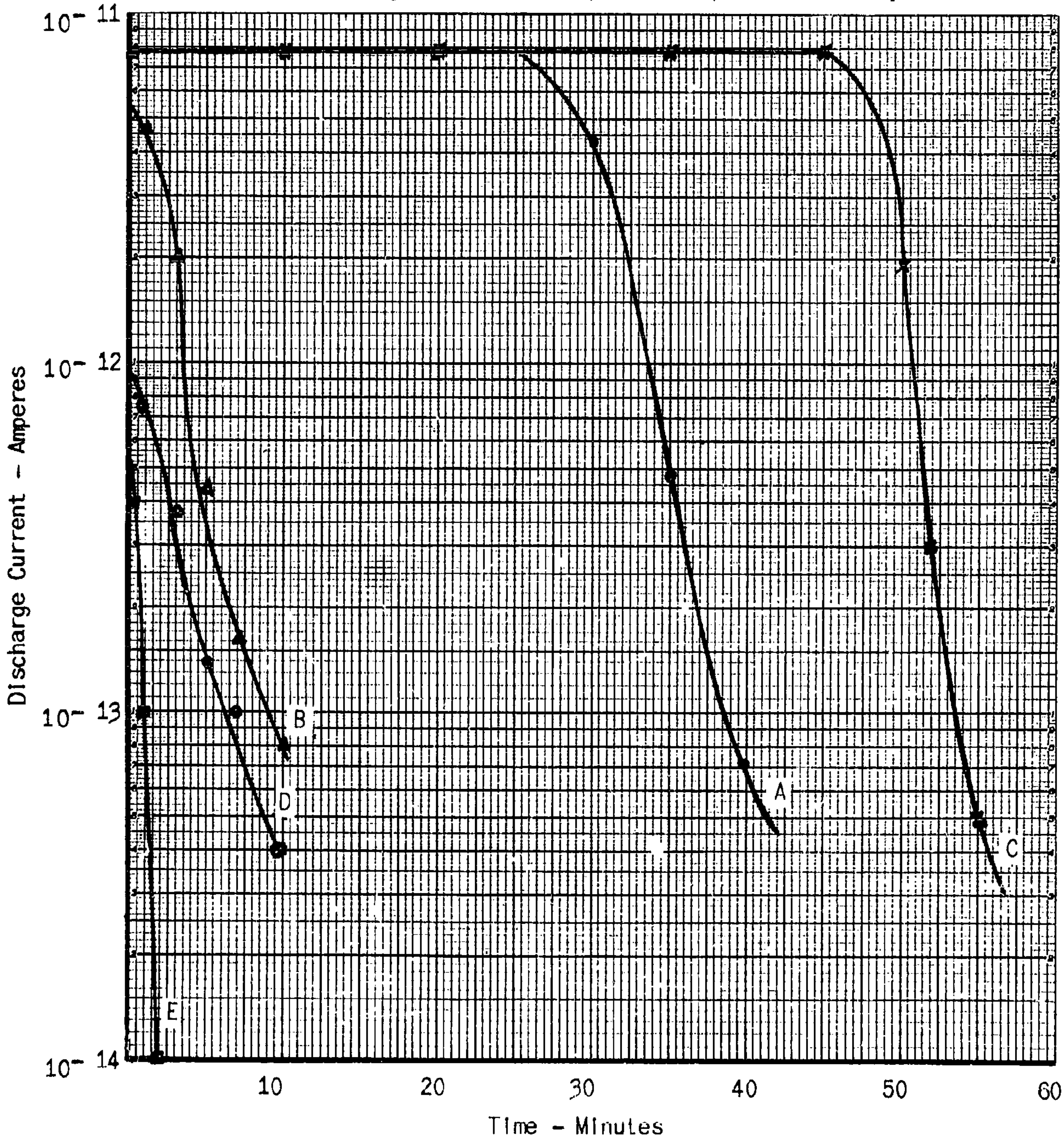
FIGURE 9

RADIOACTIVE DISCHARGE OF VINYON FIBROUS MATS

Curve A - Original Discharge
Curve B - Discharge After 3 1/4 Hour Recovery Period
Curve C - Discharge After Application of Frictional Surface Charge
Curve D - Discharge After 1 Hour Recovery Period
Curve E - Discharge of Second Sample After 3 Hour Recovery Period



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obtained from the same sample after one hour of recovery. As a final test in this series, a second sample was discharged and allowed to regain for 3 hours. In this test, more care was taken to prevent any jarring or movement of the sample as the source was removed and replaced. Curve E shows the discharge current obtained after this 3-hour recovery period.

This series of experiments demonstrates the extreme ease of frictional electrification of the Vinyon material, since rubbing the surface of a discharged mat with a glass rod produced a greater degree of electrification than was originally present. At first glance, it appears that the surface charge did undergo a certain amount of regeneration during the storage periods. In reality, however, this regeneration was probably due to slight amounts of frictional electrification as the sample moved against its support while the radioactive source was removed and replaced. Curve E of Figure 9 bears out this premise, in that the discharge was much smaller, in spite of a longer regeneration time.

b. Retention of Surface Charge. Another factor which appeared to relate the surface-charge characteristics of Vinyon to electret behavior was the apparent ability of Vinyon to maintain its charge for long periods of time. In order to test this ability, a sample was mounted in the Faraday cage, and measurements of surface charge were made at periodic intervals until no charge could be detected. It was found that the charge decayed to zero in approximately two weeks. A second test was run in similar fashion, except that the cage was opened to freely moving air. In this case, neutralization took place more rapidly, the charge decreasing to zero in approximately 6 days. (See Figure 10.)

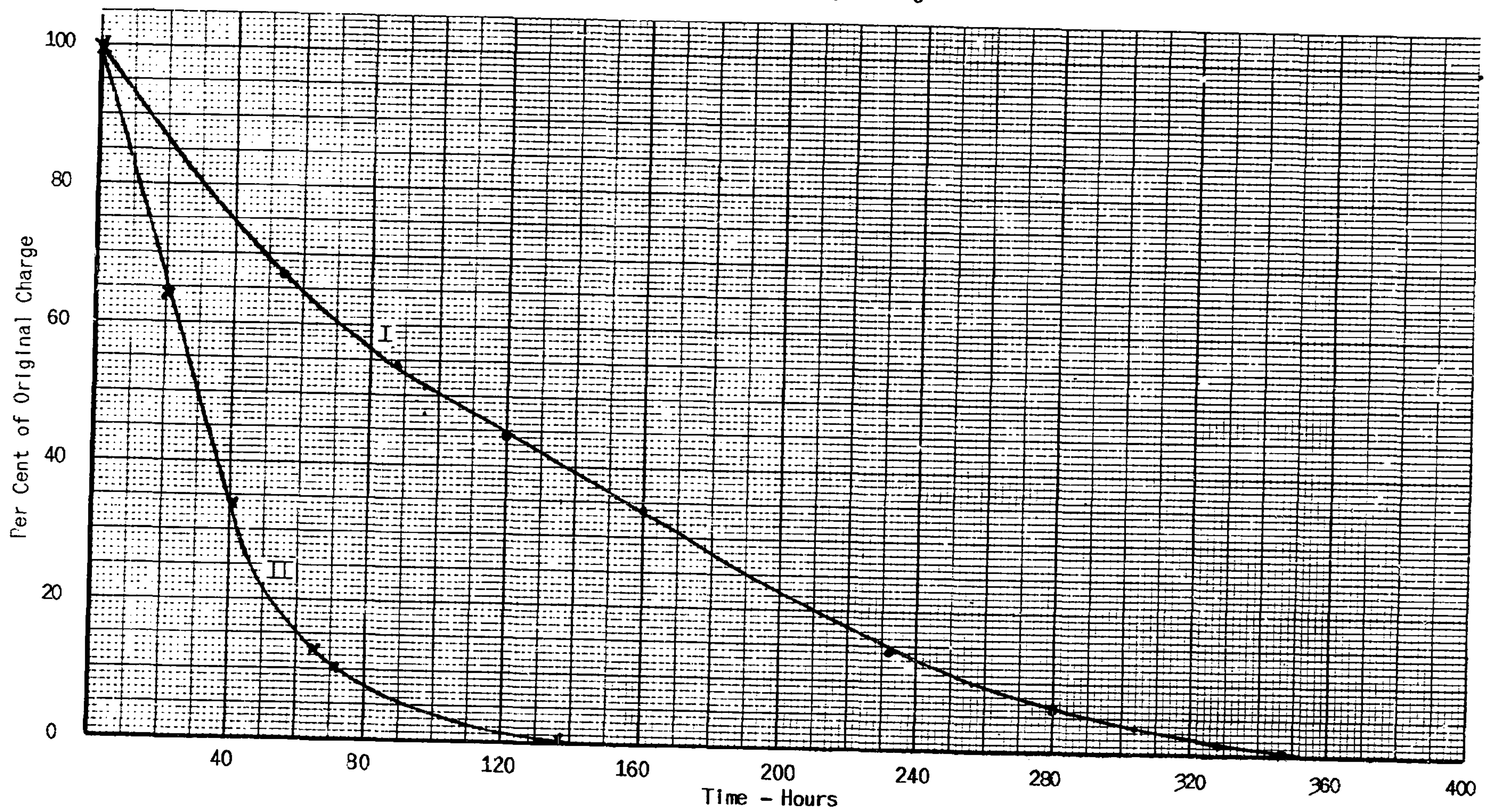
This evidence, in conjunction with the observed ease of frictional electrification, indicates that the apparent persistence of the observed surface charge is not so much due to the mat actually maintaining its charge for long periods of time, but rather to rapid regeneration whenever the mat is handled.

c. Effect of DOP Smoke. After testing a Vinyon mat with DOP, it was noted that the physical properties are altered. The mat loses much of its loose fibrous structure and becomes more of a homogeneous sheet. The fact that dioctyl phthalate is an excellent plasticizer for Vinyon could conceivably account for some of the observed changes, but it was of interest to determine the effect of DOP smoke on the electrical properties of the mat. After subjecting a Vinyon filter pad to DOP, it was found that the ability of the mat to hold a surface charge was greatly reduced. Tests showed that even a relatively high charge, applied by rubbing with a glass rod, leaked

FIGURE 10

RETENTION OF SURFACE CHARGE OF VINYON MATS

I - Sample Mounted In Closed Faraday Cage
II - Cage Opened To Freely Moving Air



off in a matter of a few minutes. This fact indicated that the electrical resistance of the material is greatly reduced by the action of the oily aerosol. By using the electrometer and shunt apparatus, an indication of the change in electrical resistivity was obtained. Samples of both the virgin mat and the DOP-treated mat were placed between brass plates, and a 1.5-volt potential was connected across them. The current produced was detected with the electrometer, and the resistance was calculated from Ohm's law. It was found that the resistance of the DOP-treated mat was approximately 10^{12} ohms, while that of the virgin material was too high to measure. This result indicates that the electrical resistance of Vinyon is reduced by the presence of DOP, by at least two orders of magnitude, and possibly by much more.

It was found that if a DOP-loaded mat is washed free of the oil with carbon tetrachloride, the original ability to hold a surface charge is restored. In spite of this fact, however, the high filtration efficiency is not restored, even when a high surface charge is purposely applied by rubbing the material with glass immediately before testing.

The results of the experiments enumerated above reveal several important facts about the electrified Vinyon microfibers. First, it would appear that the surface charge itself is not the result of an electret mechanism. Instead, it is merely due to frictional electrification caused by handling of the material. While this charge outwardly appears to be quite permanent, experiments show that it decays to zero in a relatively short time and shows no tendency to regain unless it is physically handled. It is probable that the high electrical resistivity of Vinyon accounts for the observed phenomena relating to the surface charge. The aspect of the problem which is still unexplained is the reason for lack of effect upon the filtration behavior of Vinyon when the surface is discharged with radiation. This and other evidence leaves no doubt that filtration ability is completely independent of the presence or lack of a charged surface. Therefore, the question remains as to what is the cause of the characteristic filtration curve of Vinyon.

2. Filtration Behavior

As stated above, the anomalous filtration behavior of Vinyon, as shown by the curve of Figure 8, is unaffected by low-intensity dosages of radioactivity, in spite of the complete neutralization of the surface charge. In order to ascertain whether the initial higher efficiency of the material was due to other electrostatic forces, further attempts were made to affect the filtration behavior with discharging mediums. It was found that passing humid air through the mat for 30 minutes prior to testing does cause a lowering of the initial efficiency, although the general shape of the curve is unchanged.

(See Figure 11.) This behavior is consistent with the hypothesis that electrical factors other than the surface charge are involved. A similar test, in which the change in surface charge was measured during the passage of humid air, showed that the rate of loss of charge is substantially increased, but that the charge is not significantly decreased in 30 minutes. Accordingly, it was decided to attempt to discharge the filter with a high-intensity radioactive source. A 40-millicurie strontium^{90} source (a beta-ray emitter) was obtained. The source is approximately 10,000 times more intense than the Co^{60} used in previous experiments. Several discharge tests were run, in which Vinyon mats were exposed to the Sr^{90} for varying periods of time and subsequently tested on DOP. Figure 12 shows the results of this series, which are plotted as the change with time in the quality factor

$$E = \frac{-100 \log \frac{P}{100}}{\Delta p}$$

where P = Percent penetration;

Δp = Pressure drop, in millimeters of water;

Smoke flow rate = 28 ft/min.

It may be seen from Figure 12 that the high-intensity radiation does have a significant effect upon the aerosol filtration characteristics of Vinyon. Again it may be seen that, although the initial efficiency is continually lowered with increasing exposure to radiation, there is still a slight decrease of efficiency with time; this fact indicates that some other factor is probably accounting for at least a part of the filtration behavior. It had been noted that the change in efficiency with time was accompanied by a decrease in pressure drop. An experiment was set up, therefore, in which the change in pressure drop was carefully measured as a function of time. The results of this test are shown in Figure 13. It may be seen that the pressure drop decreases almost linearly throughout the test, so that no correlation with the initial portion of the efficiency curve is possible. It seems probable that the fibers are wetted and drawn together by the DOP during the test, so that the effective fiber diameter is increased and the pressure drop reduced. This action, in turn, may cause a decrease in efficiency, but it is likely that the decrease is only a small portion of the total.

The fact that filtration efficiency is affected by both humidity and radiation leads to the conclusion that some sort of internal electrification is involved in Vinyon behavior. Whether the mechanism is related to electret action or to some other phenomena is the next logical question.

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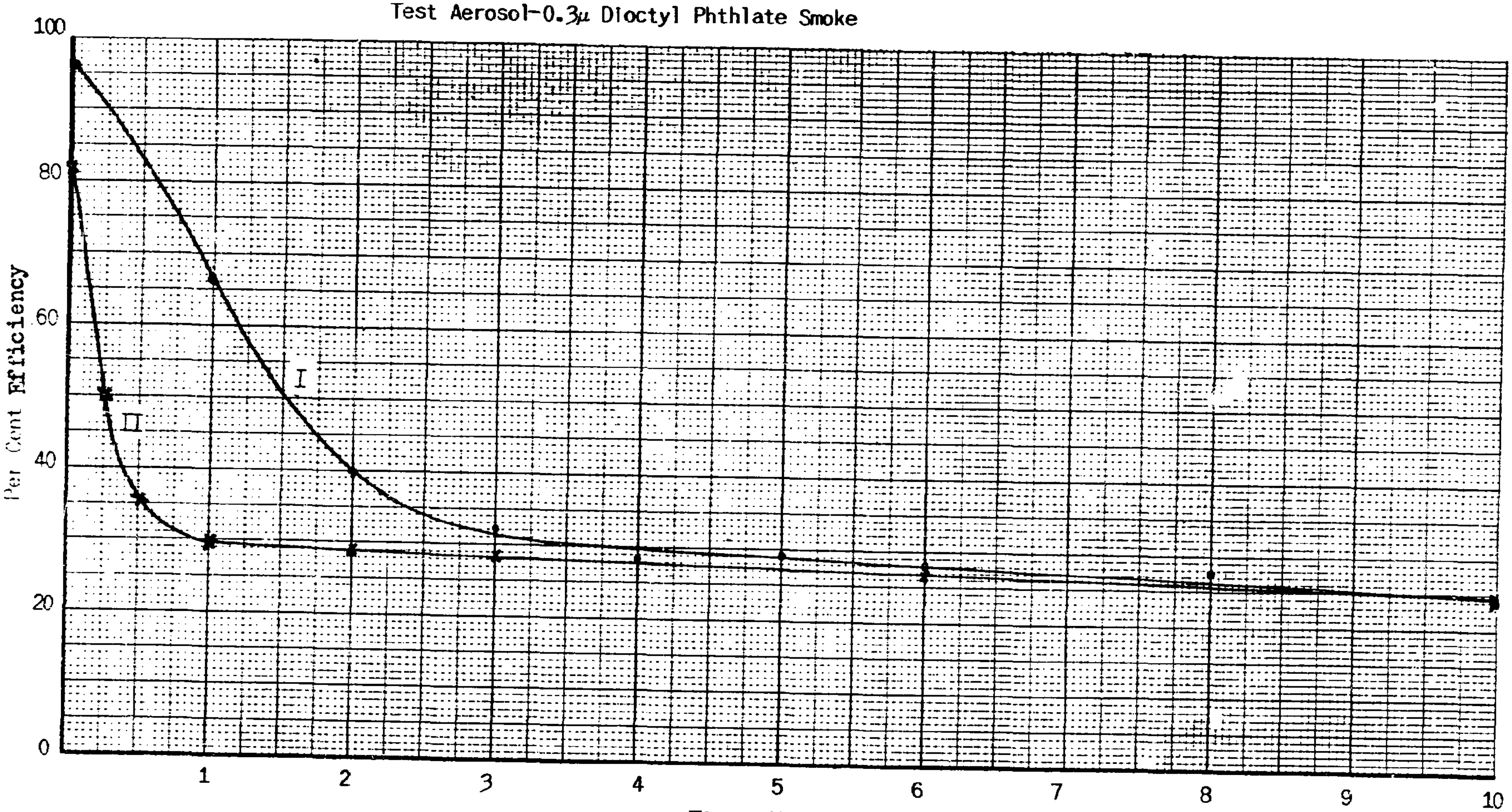
FIGURE 11

EFFECT OF HUMID AIR ON VINYON FILTRATION ABILITY

I – Control Vinyon
II – Vinyon Subjected To Flow of Humid Air For 30 Minutes Prior To Testing

Test Aerosol-0.3μ Dioctyl Phthlate Smoke



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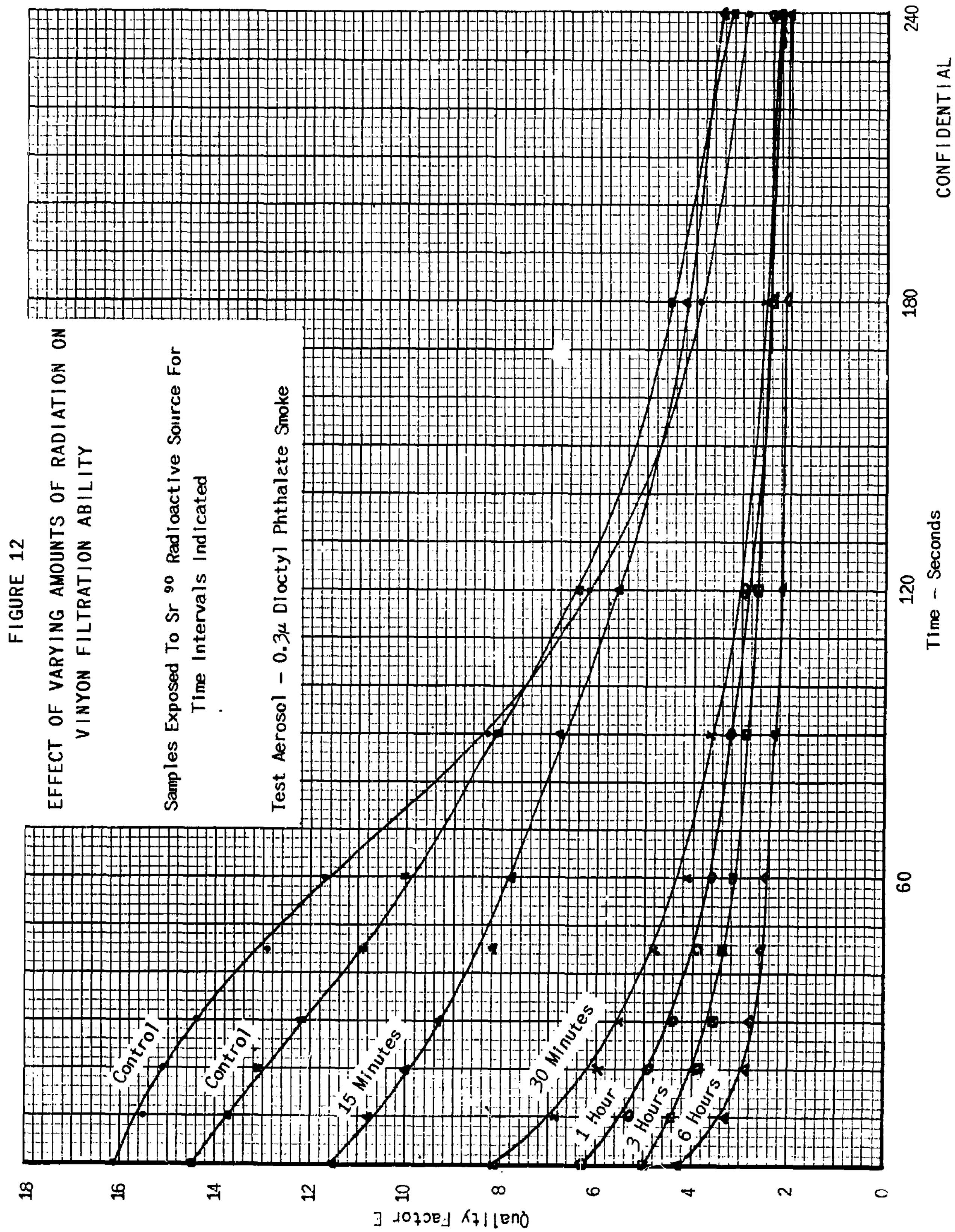

FIGURE 12

EFFECT OF VARYING AMOUNTS OF RADIATION ON VINYON FILTRATION ABILITY

Samples Exposed To Sr 90 Radioactive Source For Time Intervals Indicated

Test Aerosol - 0.3μ Dioctyl Phthalate Smoke

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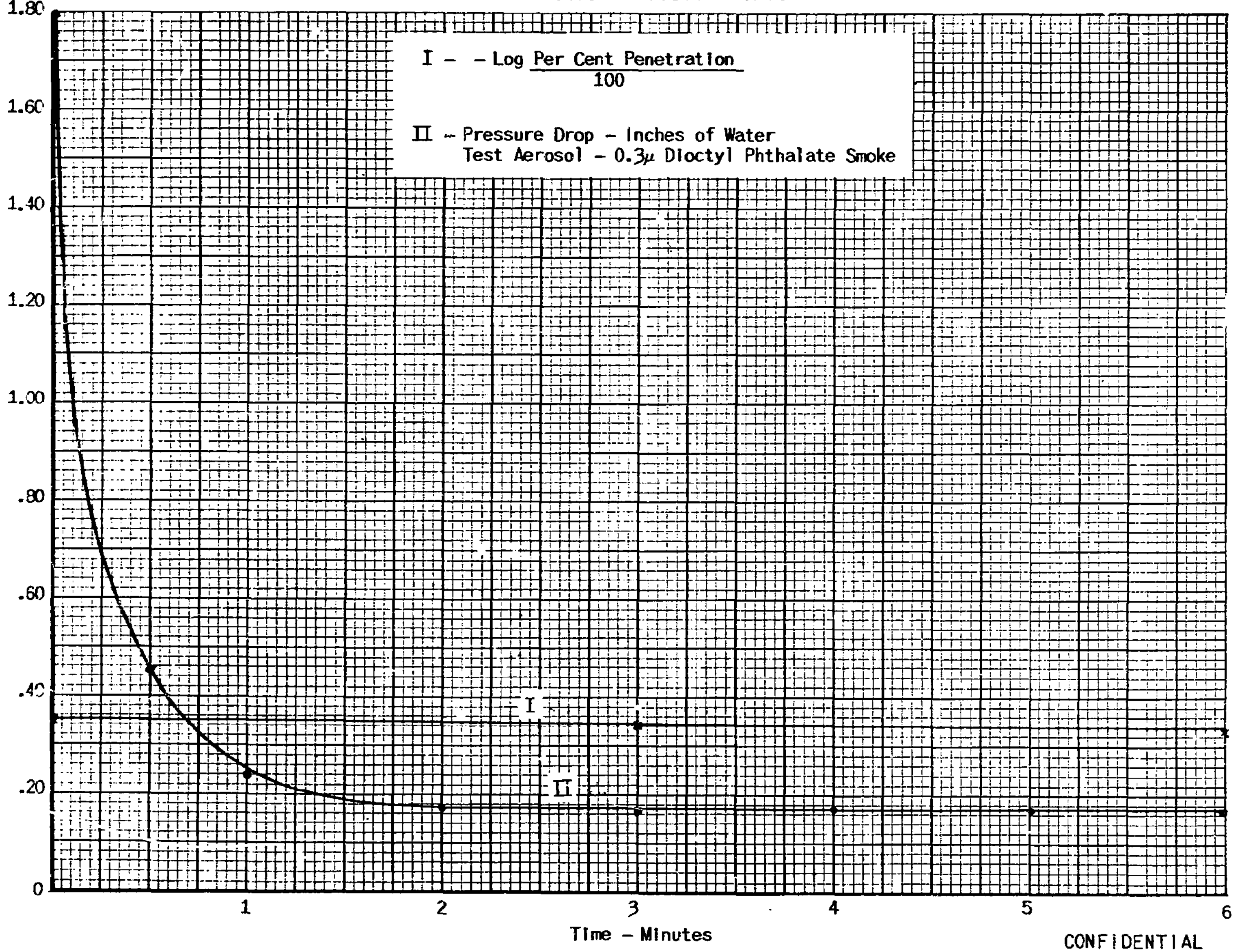
FIGURE 13

VARIATION OF PRESSURE DROP AND SMOKE PENETRATION WITH TIME
AMERICAN VISCOSE VINYON



3. The Internal Electrification

The effect of discharging Vinyon with Sr^{90} was further studied, in order to determine if the internal electrification is the result of electret-type action. This investigation was done by discharging samples and storing them for varying lengths of time before testing on DOP. If electret mechanisms were involved, it would be expected that the storage interval would allow the internal electrification to regenerate, and the filtration efficiency would also be expected to regenerate. None of the samples tested, including some that were stored for several weeks between discharge and testing, showed a significant regain of efficiency.

A similar series of tests was run with samples of Vinyon which had been washed with carbon tetrachloride. This treatment also destroys the high initial efficiency, without any apparent harm to the fibrous structure or the external electrical properties. Again the results of this series showed that there was no tendency for the original filtration ability to regenerate.

The effect of vigorously handling discharged mats was also studied. Samples discharged with the Sr^{90}, and others washed with CCl_4, were subsequently handled vigorously and rubbed with glass to accomplish as much frictional electrification as possible. In neither case, however, was the filtration efficiency regenerated. This fact substantiates the previous conclusion that aerosol filtration is independent of surface charge in this case, but it does not explain the actual mechanisms involved.

Another attempt to observe a regain of charge was made by examining the behavior of single Vinyon fibers mocroscopically. The special cells described in Section IV were used in this investigation. After the fibers were mounted and their deflections were measured, the cells were exposed to radiation, from either the cobalt or the strontium source, until the deflection of the fiber was reduced to zero. The cells were then examined at periodic intervals, in order to observe any regain of charge. Of the 29 fibers tested, 19, or 65 percent, showed some degree of re-electrification. (See Table I.) In all but one case, however, the amount of regain of charge was very small, so that it is difficult to draw any definite conclusions. The original charge was usually of negative polarity, and presumably its magnitude was largely dependent upon the amount of physical handling it received in the mounting process. Most of the fibers which did show any re-electrification showed a positive polarity. It is also interesting to note that the one fiber which showed a large recovery effect showed no tendency to lose its charge with time, and regained appreciably a second time following a second discharge. (See Figure 14.)

TABLE I

BEHAVIOR OF SINGLE VINYON FIBERS

Sample Number	Initial Polarity	Deflection (Microns)	Discharge Source	Time After Discharge (Hours)	Recovery	Polarity	Deflection (Microns)	Percent of Original	Mounting Support
Original	Negative	540	Co^{60}	70	Yes	Positive	356	66	Glass
1	Negative	435	Co^{60}	114	No	-	-	-	Copper
2	Negative	>1500	Co^{60}	114	No	-	-	-	Copper
3	Negative	230	Co^{60}	114	Yes	Positive	<5	1	Copper
4	Negative	180	Co^{60}	114	No	-	-	-	Copper
5	Negative	390	Co^{60}	114	Yes	Positive	14	3	Copper
6	Negative	1500	Co^{60}	88	No	-	-	-	Copper
7	Negative	500	Co^{60}	200	No	-	-	-	Copper
8	Positive	210	Co^{60}	200	No	-	-	-	Glass
9	Positive	340	Co^{60}	70	Yes	Positive	14	3	Copper
10	Negative	900	Co^{60}	70	Yes	Negative	<5	<1	Copper
11	Negative	770	Co^{60}	70	Yes	Positive	21	3	Copper
12	Negative	440	Co^{60}	70	Yes	Positive	<5	1	Glass
13	Negative	420	Co^{60}	70	Yes	Positive and Negative	5	1	Copper
14	Negative	380	Sr^{90}	70	Yes	Positive	<5	1	Copper
15	Negative	1000	Co^{60}	72	Yes	Positive	7	1	Glass
16	Negative	280	Co^{60}	72	No	-	-	-	Copper
17	Negative	105	Co^{60}	72	Yes	Negative	5	5	Copper
18	Negative	380	Co^{60}	72	Yes	Positive	7	2	Copper
19	Positive	130	Co^{60}	72	No	-	-	-	Glass
20	Negative	420	Co^{60}	72	Yes	Positive	21	5	Copper
21	Negative	700	Co^{60}	72	Yes	Positive	7	1	Copper
22	Negative	>1500	Co^{60}	100	Yes	Positive	14	1	Glass
23	Negative	>1500	Co^{60}	100	No	-	-	-	Glass
24	Positive	210	Sr^{90}	100	Yes	Positive	14	7	Copper
25	Negative	140	Sr^{90}	100	Yes	Positive	7	5	Copper
26	Negative	70	Sr^{90}	100	Yes	Positive	<5	5	Copper
27	Negative	560	Sr^{90}	100	No	-	-	-	Copper
28	Negative	1000	Sr^{90}	100	Yes	Positive	10	1	Copper

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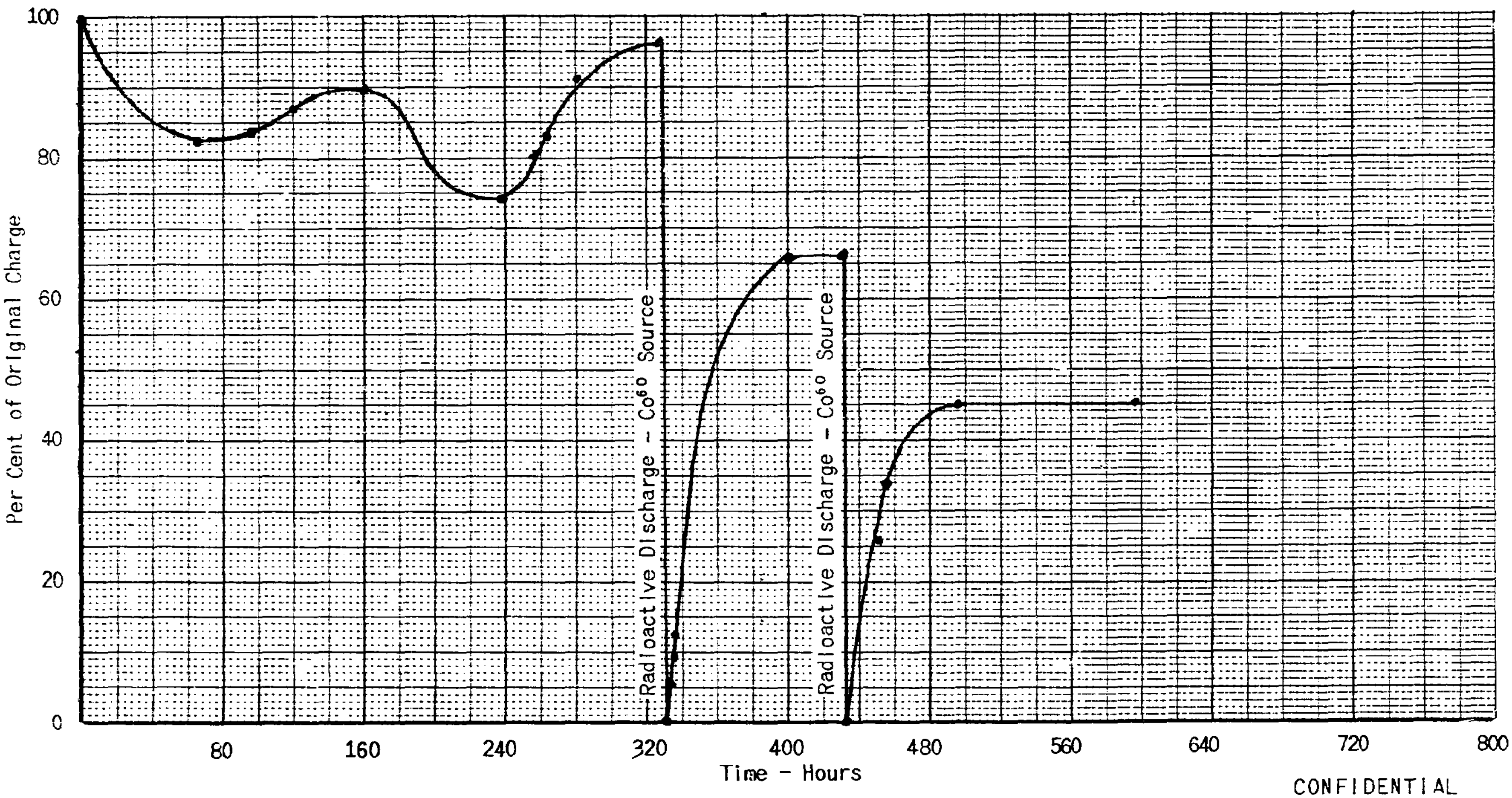
FIGURE 14

SURFACE CHARGE CHARACTERISTICS OF SINGLE VINYON FIBER



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On the supposition that some mechanism, other than surface neutralization of charge due to the ionization of the air, might be taking place, it was decided to attempt to discharge the Vinyon mat in vacuum. If discharge were occurring as a result of gas-phase neutralization, it would be expected that the filtration efficiency would be uneffected in vacuum. If, on the other hand, some other phenomena affecting the solid resin were occurring, it would be expected that the behavior would be the same in vacuum as in air. This experiment was expected to distinguish between the effect of charge neutralization caused by ionic conduction in air and other possible effects[12] resulting from structure damage occurring in the fiber itself caused by radiation from the Sr^{90}. Figure 15 shows the results of a discharge in which the pressure was reduced to approximately 1 mm Hg. It may be seen that the discharge is considerably decreased in the absence of air.

The results of this test are therefore consistent with the theory that discharge occurs as a result of ionization of the air and subsequent neutralization of charge. However, since the pressure was reduced to only 1 mm, and since some decrease in efficiency did occur, these results cannot be termed conclusive. It is possible that a combination of factors is accounting for the observed behavior, and that some of the properties of Vinyon are being permanently affected. Without more work, therefore, it is impossible to evaluate the over-all effect of high-intensity radiation on Vinyon.

4. The Bounce-off Effect

It was proposed that information about the role of bounce-off, described in Section III, in Vinyon filtration behavior might be investigated by testing a discharged filter while an electric field was applied across the mat. This would mean the bounce-off effects would be eliminated, and the efficiency should increase. Figure 16 shows the result of such a test, in which the mat was tested in a constant field of 8.5 kv/cm. Figure 17 shows the results of a similar test, in which the field strength was varied throughout the experiment, as shown. Although these results are consistent with the bounce-off theory, they are not conclusive. Other factors, such as induced charges on the fibers or charging of the aerosol droplets by corona discharge, could be accounting for the increased efficiency when the field is applied. Further refinements should be carried out, in order to make the results conclusive.

Another attempt to observe bounce-off was made by testing a filter unit made up of packed steel wool. This filter was tested with the fibers coated with a thin layer of DOP; results were compared with those of a test made when the fibers were clean. If any bounce-off effects were present in this case, they were not large enough to be measured.

FIGURE 15

FILTRATION BEHAVIOR OF VINYON AFTER EXPOSURE TO RADIOACTIVITY IN VACUUM

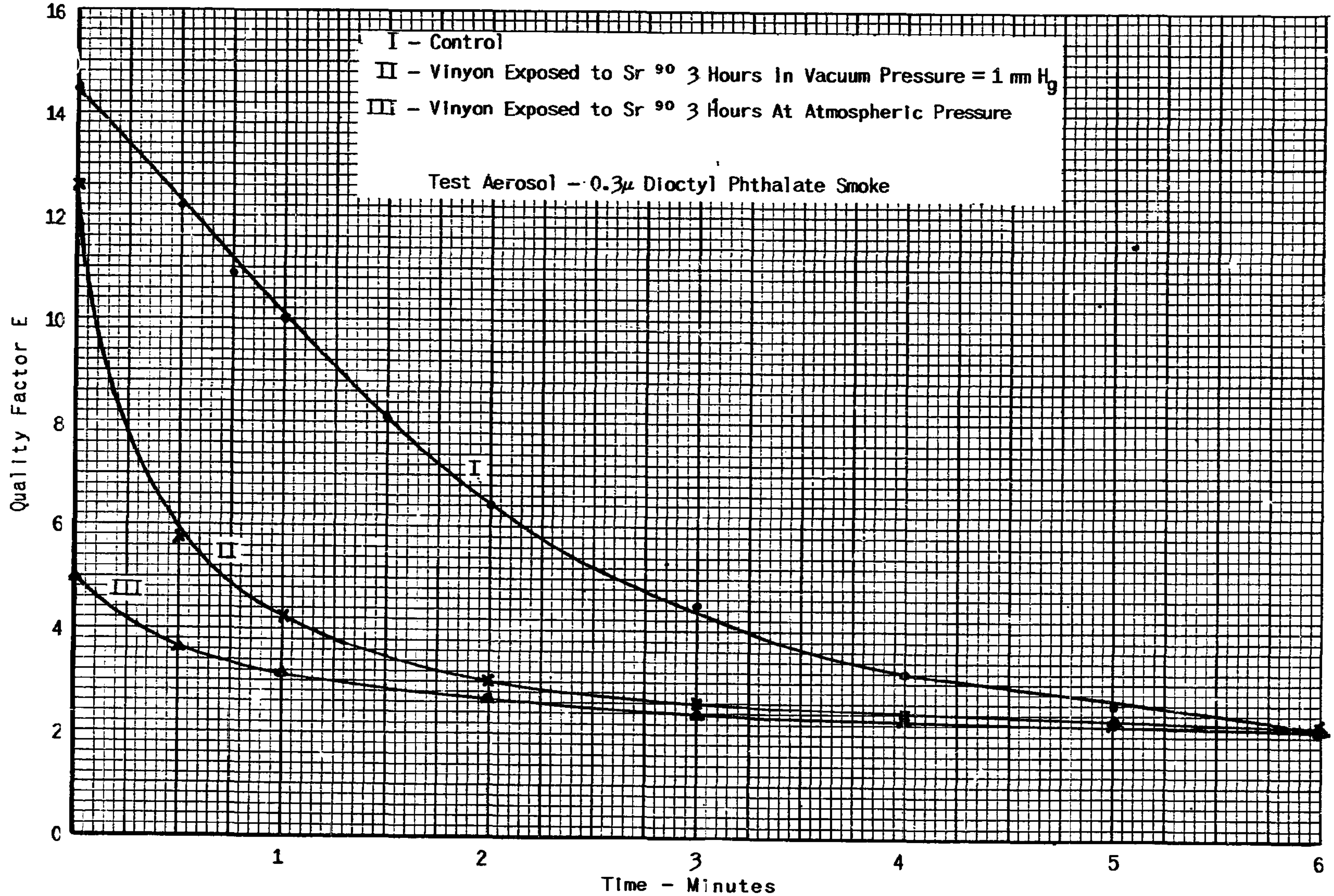

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FIGURE 16

EFFECT OF CONSTANT ELECTRIC FIELD ON FILTRATION BEHAVIOR OF VINYON

I - Normal Vinyon Behavior
II - Discharged Vinyon Behavior
III - Discharged Vinyon Tested in Constant Field Of 8.5 kv/cm
Test Aerosol-0.3μ Dioctyl Phthalate Smoke

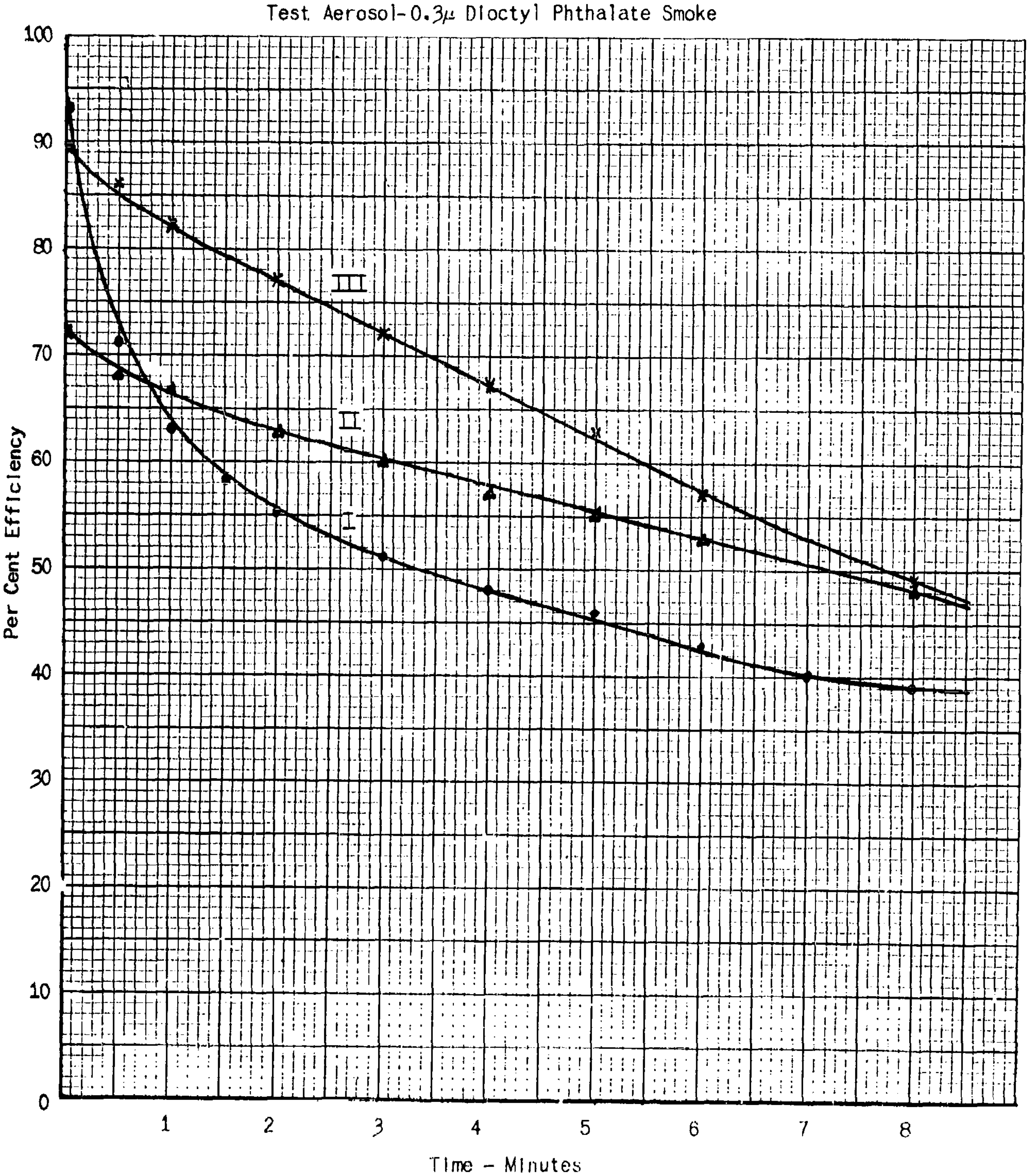

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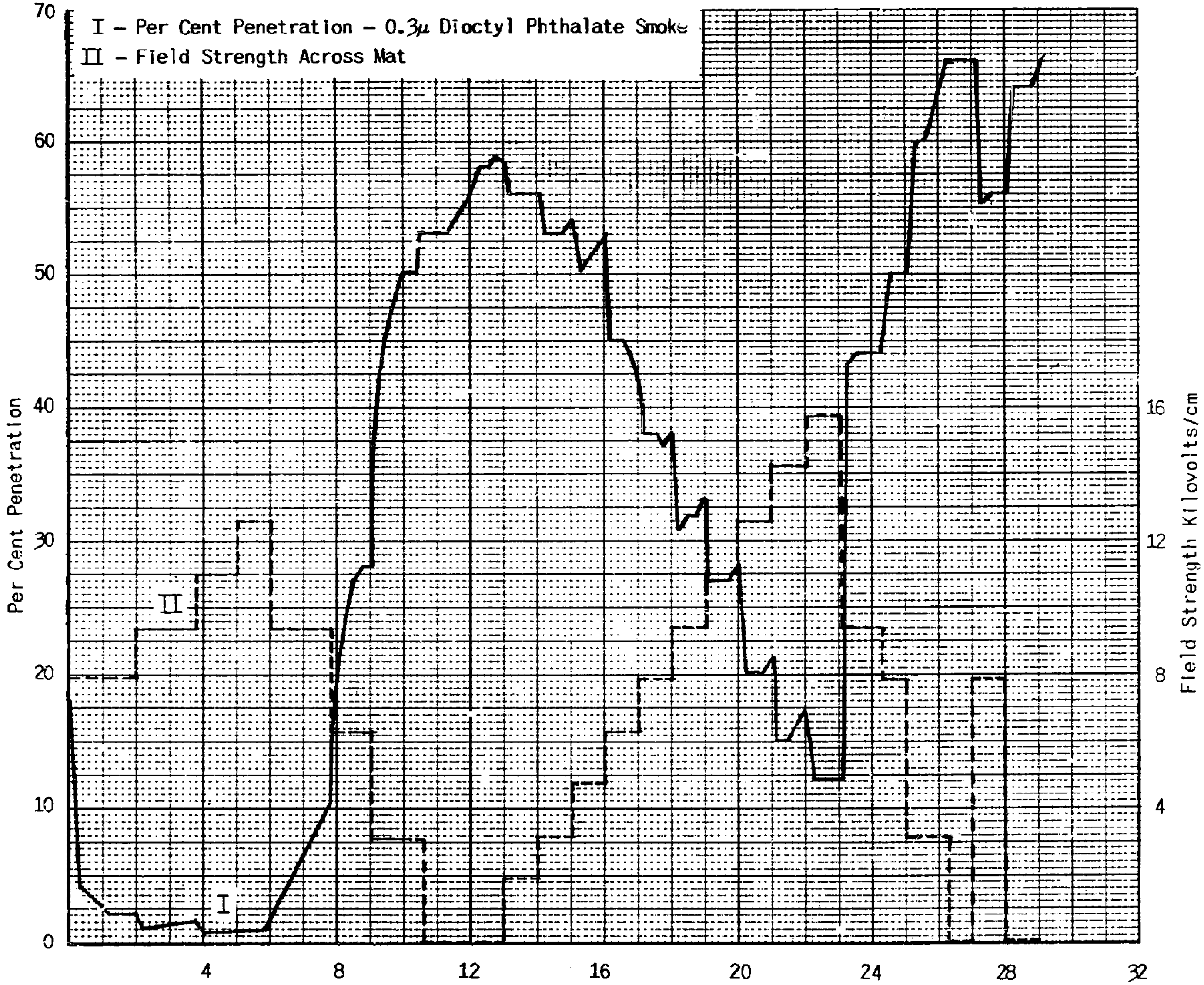
FIGURE 17

EFFECT OF VARYING ELECTRIC FIELD ON FILTRATION BEHAVIOR OF VINYON



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It is still not known what effect, if any, bounce-off has on aerosol filtration, particularly in the case of Vinyon. In future work, it should be kept in mind, however, that such a possibility does exist, and that the effect may be very significant.

5. Vinyon Electrets

In the early stages of experimental work on this contract, attempts were made to form electrets from the VYHH vinyl resin from which the Vinyon fibers are made. It was found at this time that temperatures sufficiently high to melt the resin also caused excessive thermal decomposition, so that all attempts to make electrets failed.

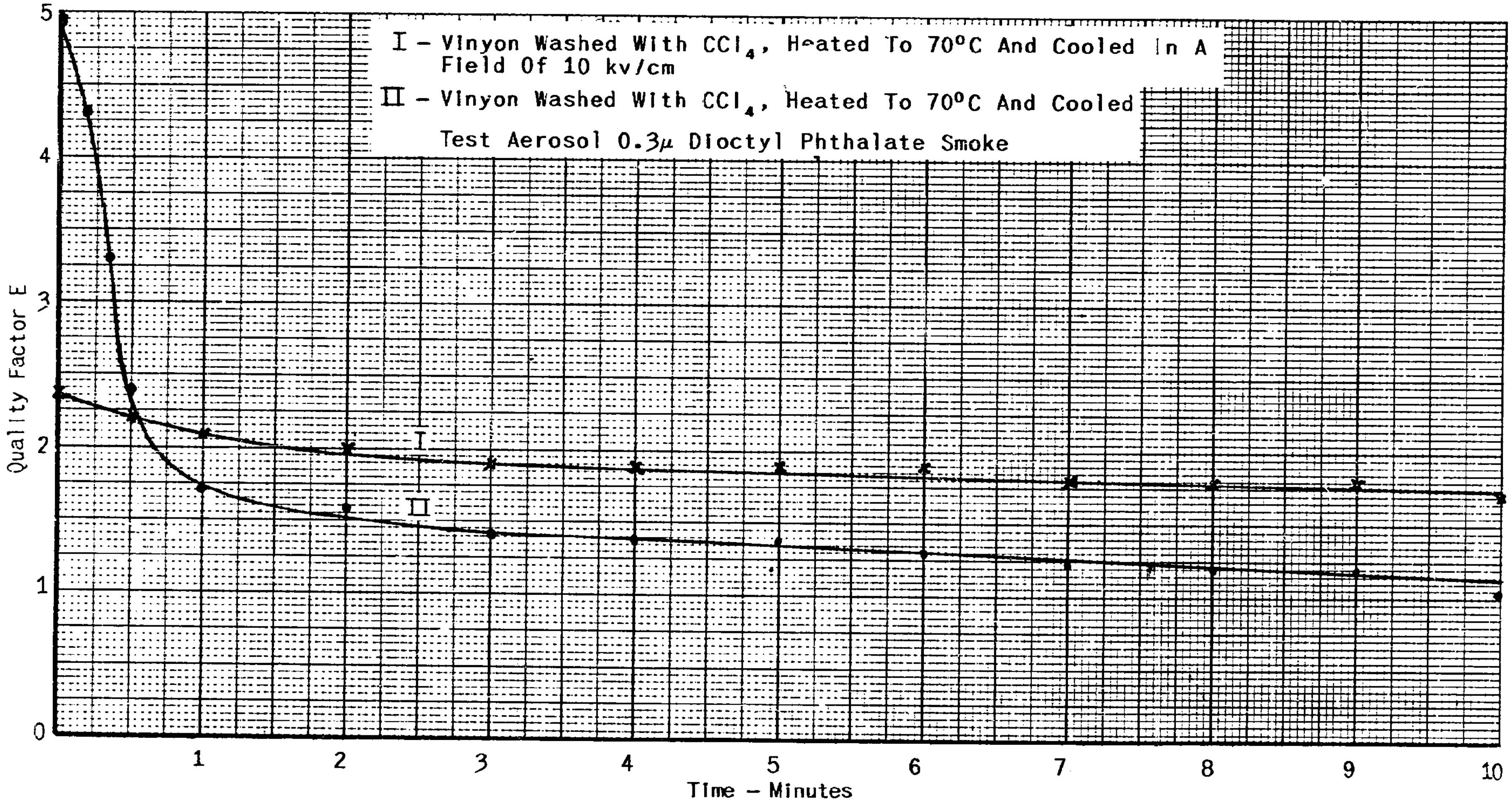
In the final weeks of experimentation, a different approach to the same problem resulted in some interesting observations. Unfortunately, time did not permit a thorough evaluation of these results. It was found that when the powdered VYHH resin is heated in an oven to 110°C and cooled in a field of 10 kv/cm, the resin fuses together without actually reaching a fluid state and forms a disc which exhibits electret properties. That is, its surface charge spontaneously regenerates after radioactive discharge, and the opposite faces of the disc show charges of opposite polarity.

In conjunction with the experiment described above, several samples of the fibrous Vinyon mat were subjected to similar treatment. These samples were heated in an oven to 70°C; at this point the fibers soften and coagulate somewhat, and cause shrinkage of the mat. A field of 10 kv/cm was then applied across the sample until it cooled to room temperature. The resulting mats showed the same properties as the VYHH disc, in that they regained a charge on the surface after radioactive discharge, and they showed opposite polarity on opposite faces. It was found that these phenomena occurred with both virgin mats and mats washed with carbon tetrachloride to cause discharge. In addition, it was noted that in spite of the physical changes caused by the thermal treatment, the air porosity was not significantly decreased.

Because of this latter fact, it seemed possible that an interesting filter might be made in this manner. Accordingly, two samples of Vinyon were washed with carbon tetrachloride, in order to cause discharge of the internal electrification. Both samples were subsequently heated to 70°C, and one was allowed to cool in an electric field of 10 kv/cm. The resulting mats were then tested for DOP penetration. The results of these tests are shown in Figure 18. It may be seen that the sample which was subjected to electret-forming conditions shows a considerably higher initial efficiency than the control, and, in addition, the characteristic drop-off of efficiency with time is evident.

FIGURE 18

FILTRATION BEHAVIOR OF DISCHARGED VINYON AFTER APPLICATION OF ELECTRET FORMING CONDITIONS



Unfortunately, time did not permit continued experimentation on this aspect of the work, so the full significance of these results is still not known. It must be conceded, however, that the results indicate for the first time that electrets may be capable of existing in forms beneficial to aerosol filtration.

D. Resin Wool Filters

Some experimental work has been done on resin wool filters, primarily for the purpose of comparing their performance with that of Vinyon. Figure 19 shows the typical behavior of two resin wool filters when tested on DOP smoke. The performance of these filters has been found to be similar to that of Vinyon in many ways. That is, the filtration efficiency is unaffected by low dosages of radiation, but is decreased by exposure to the high-intensity Sr^{90} source. (See Figure 20.) In contrast to the Vinyon, the resin wool filters have almost no external field or surface charge present. They presumably function by means of microscopic fields, set up between resin particles and the wool fibers, which balance out over the surface of the mat so as to give a net charge on the surface of nearly zero.

It has been found in preliminary studies that the filtration performance of resin wool filters is improved if the sample is tested at a slightly elevated temperature. Figure 21 shows the results of tests in which samples were stored in an oven at 130°F for one and two hours immediately prior to testing. A similar sample was removed from the oven and allowed to cool to room temperature for a period of about two hours; in this case, the efficiency dropped down again to its normal value. It is tempting to correlate this behavior with that exhibited by disc electrets for which we observed that the charge-producing mechanism appears to be accelerated by higher temperatures.

The VYHH vinyl resin from which the Vinyon microfibers are made has been found to form a good resin wool filter when the powdered resin is dusted liberally on wool felt. Figure 22 shows a comparison of the filtration ability of a piece of untreated wool felt, the American Optical resin wool filter, and wool felt treated with 35 percent by weight of VYHH resin. The indication here is that the resistivity of the VYHH resin is extremely high. Although measurements of resistance confirm that this is true, they do not determine what the actual value in a filter is. It may be that, as in the case of the resin wool filter, this property plays a very significant role.

FIGURE 19

FILTRATION BEHAVIOR OF RESIN WOOL FILTERS

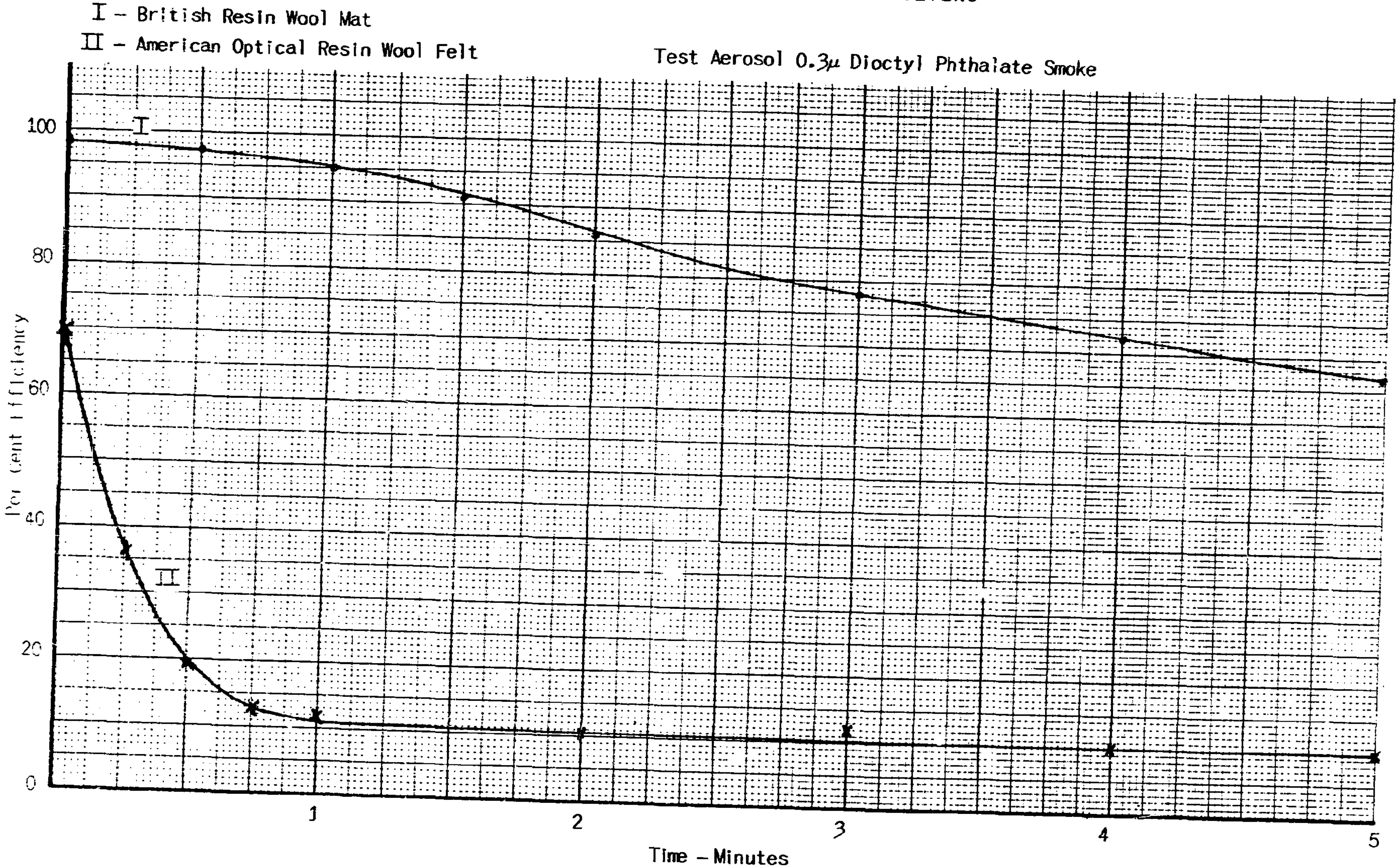


FIGURE 20

EFFECT OF RADIATION ON RESIN WOOL FILTRATION ABILITY

I - Control Resin Wool Felt

II - Resin Wool Felt Exposed To Sr ^{90} Radioactive Source For 18 Hours Prior To Testing

Test Aerosol 0.3μ Dioctyl Phthalate Smoke

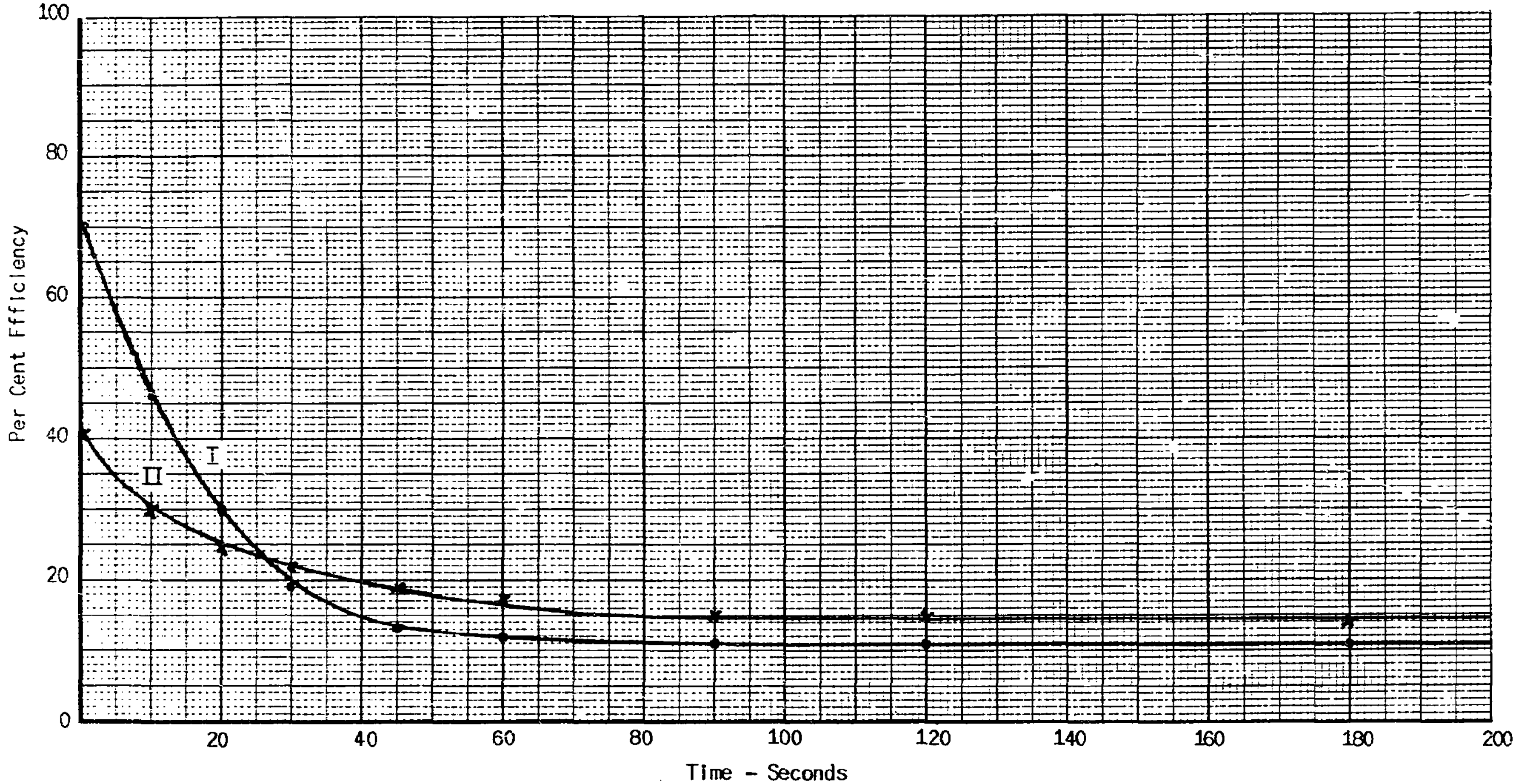


FIGURE 21

EFFECT OF HEAT ON RESIN WOOL FILTRATION ABILITY

I - Control Resin Wool Felt
II - Resin Wool Felt Heated In Oven For 1 Hour Prior To Testing
III - Resin Wool Felt Heated In Oven For 2 Hours Prior To Testing
Test Aerosol - 0.3μ Dioctyl Phthalate Smoke, Oven Temperature - 130°F

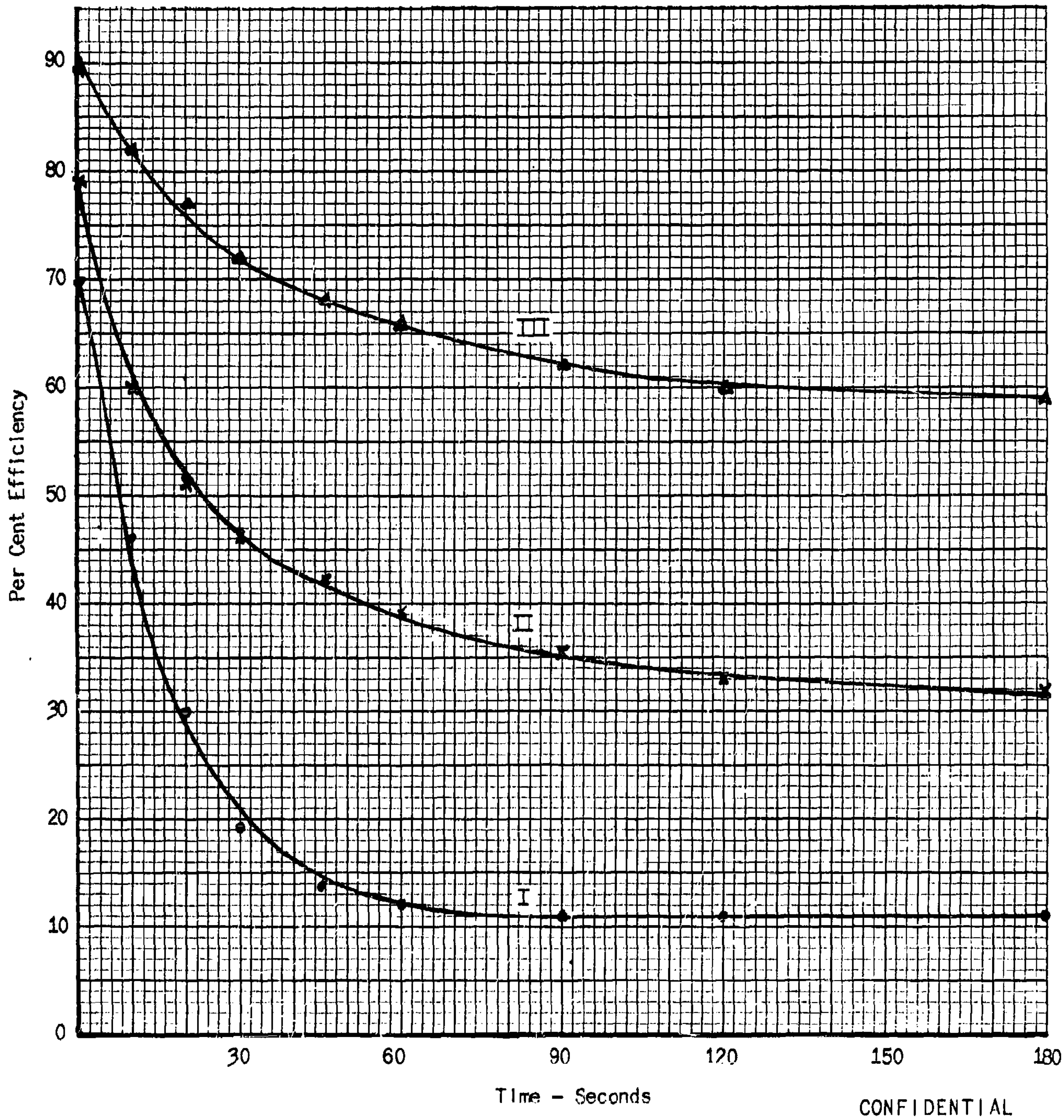
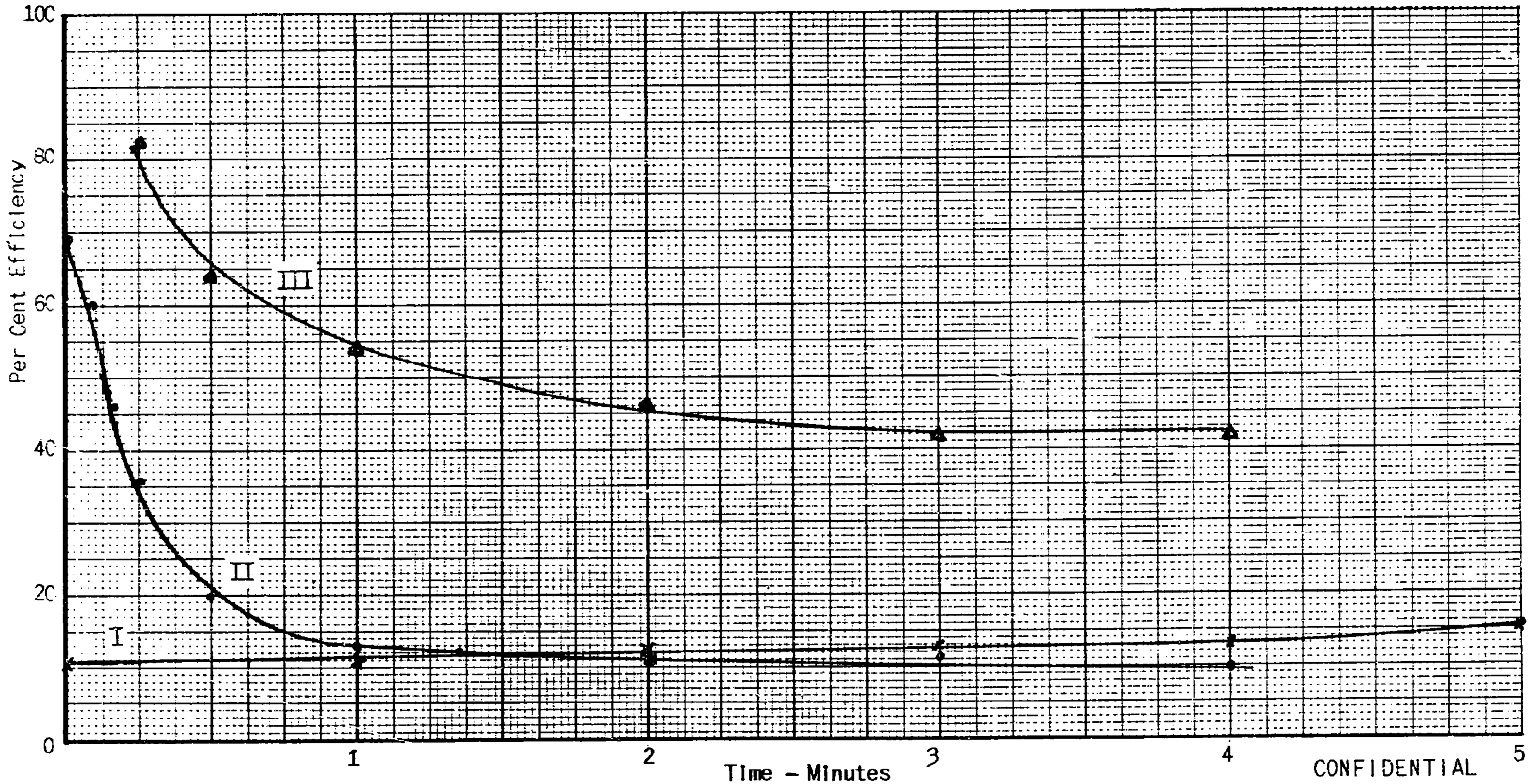


FIGURE 22

FILTRATION BEHAVIOR OF VYHH RESIN TREATED WOOL FELT

I – Untreated Wool Felt
II – Resin Treated Felt From American Optical Co.
III – Wool Felt Treated With VYHH Resin

Test Aerosol-0.3μ Dioctyl Phthalate Smoke



VI. CONCLUSIONS AND RECOMMENDATIONS

It is quite obvious from the work done on this contract that the problems involved in the development of an aerosol filter incorporating electrets are numerous and complex. Considerable effort was devoted to direct attempts to form filter units incorporating electrets in various forms. In no case, however, was the expected enhancement of efficiency observed, nor was a fall-off of efficiency with time obtained. This latter property is characteristic of electrostatic filter materials when tested on DOP smoke, and is apparently due to neutralization of charge by the conductive oil smoke. This evidence does not necessarily mean that it is not possible to form filters incorporating electrets to enhance performance, but it does indicate that the phenomena involved are not yet sufficiently well understood to allow immediate realization of successful application.

Whether or not the American Viscose microfibers derive their filtration ability through electret mechanisms is still not known. It seems reasonably certain that the high efficiencies observed are due to electrostatic action of some type, and that this action is independent of the presence or absence of an external field or surface charge. The hypothesis that electrets are responsible for Vinyon behavior is an attractive one in many respects, but it is difficult to isolate and detect any concrete evidence supporting such a mechanism. On the other hand, it is also difficult to propose an alternative mechanism which will explain the observed phenomena as satisfactorily.

Single Vinyon fibers have been observed to regain their charge in a fashion similar to that which might be expected from electrets. This regain of charge has been very small, however, so that it is not possible to say whether actual electret recovery or some sort of leakage of charge to the fiber was taking place. The fact that the fibers usually regained to a positive polarity rather than to the negative polarity originally present indicates the possibility that a surface charge could have been masking the electret charge. On the other hand, it would be expected that a dipolar charge distribution would be evident if electrets were involved, and no such observations have been made in any of the work on Vinyon.

Work on the gross properties of the virgin mat has led to conflicting data and results. In no case has an electret-type regain of charge been observed, but a very definite degree of internal electrification appears to be present. In many ways, this internal phenomenon resembles that which is found in resin wool filters. That is, the filtration behavior of the two

media is similar, and radiation dosages of the same order of magnitude are necessary to cause discharge. In neither case does a surface charge indicate the presence of this internal electrification. With the resin wool material, the behavior can be quite satisfactorily explained through the mechanism of frictional electrification due to mechanical handling of the mat. As can be observed with many substances, the two dissimilar materials, wool and resin, are capable of generating frictional charges when they are rubbed against each other. It also seems logical that this type of electrification would produce no external field or net charge due to the random distribution of resin and wool throughout the filter. Although it is difficult to explain the long shelf life of the units, it is possible that conditions are such that an effective resistivity high enough to prevent significant loss of charge is present.

With the Vinyon material, however, the internal structure does not appear to be analogous. Although frictional charges can be readily generated, these charges appear as a net surface effect and have no influence upon the filtration ability of the material. The fact that discharged mats cannot be regenerated by mechanical handling indicates that there must be two distinct types of electrification present. The first is the surface charge, or external electrification, which is presumably frictional. The second is the internal electrification which is responsible for the filtration characteristics of Vinyon. This latter is not frictional and may occur as a result of the conditions of manufacture.

A possible explanation for the internal electrification is that something related to electret formation does occur during manufacture, but that these electrets are incapable of regenerating more than a negligible amount of their electrification. This might result in a visible regain, as exemplified by the individual fiber studies, but the regenerated strength might be insufficient to affect the filtration ability. This is conceivable in that the properties of fibrous electrets are unknown.

If such a mechanism is indeed present, it becomes obvious that one of the most desirable of the anticipated features of electret filters is missing, i.e., the ability to regenerate charge after exposure to a discharging medium. Without this feature, it appears that any filter functioning by means of electrostatic action will be subject to certain inevitable disadvantages. These disadvantages have been recognized in the case of the resin wool filters, and presumably are the reasons for the rather limited use to which the filters have been put.

Even if an electret filter did show the ability to regain its charge, it is probable that it would still tend to lose at least a part of its efficiency when exposed to discharging conditions such as ionizing radiations, high humidity, or conductive aerosols. At this point, however, much of what can be said must still be based on conjecture.

In the final stages of experimental work, it was found that by subjecting Vinyon to thermal and electrical conditions favorable to the formation of electrets, a filter could be made which, outwardly at least, appears to function by means of electret-type action. Although insufficient time was available to allow a complete analysis of the observations, it appears for the first time that the Vinyon resin is capable of forming electrets and that these electrets exist in a form which may be readily adapted to aerosol filtration.

Without more experimentation, it is difficult to evaluate these results in terms of the properties of virgin Vinyon material. It may be that the original manufacturing conditions accomplish essentially the same results as have been obtained in this latter experimentation, except that the external electret properties are not present, due to the random distribution of individual fibers. On the other hand, this may be an entirely different mechanism resulting in a product with similar behavior. It is probable that continued experimentation on this aspect would lead to a clearer over-all picture of the properties of Vinyon and the mechanisms by which it functions as a filter.

In the light of our present knowledge, therefore, it appears that continuation of this work for another year would be advantageous.

We recommend that the continued effort, while retaining the same basic objectives as the present contract, allow for a more fundamental investigation into the physical chemical phenomena involved, in order to improve the over-all understanding of the problem. It is our belief that another year of work might accomplish two things. First, considerable light might be shed upon the more basic aspects of electrostatic fibrous filter behavior. Second, a second year of work might resolve many of the unexplained problems of fibrous electrets and their potential use in aerosol filtration. Such a continuation might include the following objectives.

1. To determine the role of electrets and electrified materials in aerosol filtration media with special attention to:

   a. The mechanisms of particle collection in electrostatic filters such as the American Viscose microfibers and resin wool felts. This would necessarily include a study of such factors as charge distribution within the filter, particle size, particle-charge distribution, particle dielectric constant, temperature dependence, and other variables which might be encountered during the course of the investigation.

b. The unexplained phenomena observed during the course of the present contract, such as:

(1) The high radiation dosage necessary to affect filtration behavior of Vinyon when low dosages rapidly neutralize the external field.

(2) The failure of even extremely high radiation dosages to reduce completely the high initial efficiency.

(3) The charge regeneration behavior of single Vinyon fibers.

(4) The mechanism of the internal electrification of Vinyon.

(5) The temperature dependence of resin wool filters.

(6) The reason why nylon fibers manufactured under conditions believed to be favorable to the formation of electrets showed no electrification.

c. The properties of the Vinyon "electret" filter, including a study of such factors as:

(1) The effect of discharging mediums.

(2) The shelf life.

(3) The effect of higher field strengths during manufacture.

d. Conditions necessary for discharge or breakdown of electrostatic media, and possible methods of overcoming or limiting such breakdowns.

2. Based upon the results of 1, to fabricate and evaluate filters made up of or incorporating electret materials.

VII. APPENDIX

APPENDIX A

THE ELECTRICAL CHARACTERISTICS OF RESIN IMPREGNATED FILTERS

SUMMARY OF FINDINGS AT PORTON; PORTON REPORT #2465

W. H. Walton - 15 December 1942

1. It has been confirmed that the high efficiency of impregnated filters is due to the electrical attraction of dust and smoke particles to the fibers of the filter.

2. It is believed that the resin particles have a negative charge, and that an equally induced positive charge is to be found in the neighboring regions of the fibers, so that individual fibers and filters as a whole are electrically neutral.

3. The breakdown of impregnated filters is due to leakage or neutralization of the frictional charges on the resin particles.

4. Filters retain their electrification by virtue of the high electrical resistance of the impregnated particles, including the contact resistance between the particles and the fibers.

5. No electrical test has yet been developed which will enable the suitability of a resin for use as an impregnant to be assessed.

6. A study of the X-ray dosage-penetration characteristics appears to be a promising method of measuring the degree of activation of the filters.

APPENDIX B

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